Flight Dynamics Analysis Branch
End-of-Year Report
October 1, 2005 through December 31, 2006

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 595, in support of flight projects and technology development initiatives covering the period from October 1, 2005, through December 31, 2006. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key accomplishments and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the disciplines of flight dynamics including spacecraft navigation (autonomous and ground based), spacecraft trajectory design and maneuver planning, attitude analysis, attitude determination and sensor calibration, and attitude control subsystem (ACS) analysis and design. The FDAB currently provides support for missions and technology development projects involving NASA, other government agencies, academia, and private industry.

The contents of this report are based on input generously supplied by members of the Mission Engineering and System Analysis (MESA) Division's Flight Dynamics Analysis Branch (FDAB) at NASA/Goddard Space Flight Center (GSFC). This document will be available on the World Wide Web (WWW) at the Uniform Resource Locator (URL):

http://fdab.gsfc.nasa.gov

Flight Dynamics Analysis Branch
End-of-Year Report
October 1, 2005, through December 31, 2006

Welcome to the End-of-Year Report for Code 595, the Flight Dynamics Analysis Branch (FDAB) at the NASA Goddard Space Flight Center. This report covers the period from October 1, 2005, through December 31, 2006, and is divided into these sections:

- Flight Dynamics Analysis Branch News and Events
    - Employee and Branch Development
    - Outreach and Communications
    - Project Support (excluding Constellation and In-House Missions)
    - Future Mission Concept Development
- Space Technology 5 Launch and Operations
- Project Constellation Support
- Innovations and New Capabilities
- In-House Mission Support
    - Solar Dynamics Observatory (SDO)
    - Lunar Reconnaissance Orbiter (LRO)
    - Magnetospheric MultiScale (MMS) Mission
    - Global Precipitation Measurement (GPM) Mission
- Flight Dynamics Facility

Flight Dynamics Analysis Branch News and Events

Introduction

This section covers the news and events over 2006. This year saw the FDAB moving forward in a variety of areas ranging from project support to developing new ideas for future missions to further improving our internal and external relationships. Each article is classified into one of the following categories and features a point of contact.

- Employee and Branch Development
- Outreach and Communications
- Project Support (other than for Constellation and In-House Missions)
- Future Mission Concept Development

Employee and Branch Development

As part of our ongoing commitment to excellence, FDAB participated in employee and branch development activities across the organization. The branch hosted college summer interns, saw two of its employees successfully complete their PIP II analyses, participated in the NASA FIRST program, and began work to more closely align our strategic goals with NASA's as a whole.

College Summer Interns

As part of the 2006 college summer intern program, we welcomed Patrick Conrad and Gerardo Cruz to the branch and assigned them mentors to help them with their analysis projects. Patrick, an undergraduate student from Cornell University's School of Applied and Engineering Physics, spent the summer of 2006 analyzing ST9 Precision Formation Flying onboard navigation using GEONS and associated utilities, the use of autocorrelated process noise in an orbit determination filter, and relative/absolute navigation fusion methods. Gerardo, an Aerospace Engineering student from the Massachusetts Institute of Technology (MIT), worked on understanding the high fidelity simulator of the various control modes on the Lunar Reconnaissance Orbiter (LRO) mission. This work involves knowledge of rigid body dynamics, space environmental modeling, linear control systems, and high fidelity simulations.

PIP II—Analyzing Navigation Constellations with Orbit Determination Latency
(POC: Kevin Berry, Kevin.Berry@nasa.gov)

The purpose of Kevin's analysis was to determine which lunar constellation design gave the best results based on orbit determination latency as a metric. Orbit determination latency, which is a measure of the time needed to obtain an orbit determination solution, was used to examine several possible lunar navigation constellation alternatives for global and regional coverage of the Moon. This analysis, which grew out of the Space Communication Architecture Working

Group's (SCAWG) Navigation Team analysis, found that of the seven constellations analyzed, the 6-satellite/2-plane polar constellation produced the best results.

PIP II—Optimizing Stationkeeping Maneuvers for JWST
(POC: Leigh Janes, Leigh.Janes@nasa.gov)

The purpose of Leigh's analysis was to find a numerical technique for optimizing stationkeeping (SK) maneuver ΔV for the James Webb Space Telescope (JWST). JWST, which is an infrared space telescope currently scheduled to launch in 2013, is intended to take up station about the Sun-Earth/Moon Lagrange point L2. While useful for science, motion about the L2 point is unstable and requires periodic SK maneuvers to keep JWST in its vicinity. In order to determine a delta-V budget for the SK maneuvers, a trajectory simulation was created and four perturbation sources were introduced: solar radiation pressure error, orbit determination error, maneuvers execution error and momentum unloads. Using a one-dimensional search algorithm, minimum delta-V solutions were found in 1^{st} or 3^{rd} quadrant. Combining these solutions with the mission constraints resulted in a 43% savings. This method is applicable to any mission that intends to fly near L1 or L2.

NASA FIRST
(POC: Leigh Janes, Leigh.Janes@nasa.gov)

The NASA Foundations in Influence, Relationships, Success and Teamwork (FIRST) program is a new agency wide leadership development program for GS 11-12's. Throughout the year long development program, the FIRST participants develop their leadership skills through educational activities, group projects, and personal coaching, as well as interaction with participants from other NASA centers. There are six Goddard participants in the program, including Leigh Janes and Rivers Lamb from the FDAB.

Strategic Implementation Plans
(POC: Mika Robertson, Mika.K.Robertson@nasa.gov)

The FDAB created a team to focus on branch specific issues that would support implementation of Goddard's and NASA's Strategic Plans. In creating the FDAB Strategic Implementation Team, the branch selected personnel from the areas of Orbit and Attitude analysis as well as Operations (Flight Dynamics Facility). The team then reviewed current areas of support and analysis, and considered future work and desired areas of work expansion. With these thoughts in mind, the team drafted a Mission and Vision statement for the branch, and created six goals whose implementation would facilitate the branch's support of GSFC's and NASA's Strategic vision. These six goals focused on areas such as Management, Personnel Competency and Training, Analysis Tools and Techniques, New Work Generation, Distribution of Analysis and Information, and Operational Capabilities. The goals listed specific objectives for execution and implementation, and each goal was assigned to a branch Road Mapping Team to devise a specific implementation plan which includes implementation strategies and actions, metrics to ensure goal completion, and execution time lines. These road-mapping activities are currently underway and should be completed in Calendar Year 2007.

Outreach and Communications

The FDAB values strengthening its relationships both internally and externally. The outreach and communication activities in this section highlight some of that commitment.

New Employee Welcoming Board (Newb)
(POC: Leigh Janes, Leigh.Janes@nasa.gov)

The GSFC New Employee Welcoming Board (Newb) is an organization that works to improve the transition of new employees to the work force at Goddard. Since it's inception in 2004, members of the FDAB have been active in the organization. In the past year Newb has continued it's work with the Office of Human Capital Management by providing and updating a Goddard 101 Handbook and assisting with the new employee orientations and fairs. Most recently Newb partnered with the head of recruitment at Goddard to assist with the recruiting process. FDAB employees continue to help with the day to day running of Newb as well as its involvement with other organizations at Goddard.

TableSat
(POC: Paul Mason, Paul.A.Mason@nasa.gov)

In May of 2006, the TableSat Team participated in the Lockheed Martin's sponsored Space Day hosted at NASA Goddard. The primary goal of Space Day 2006 was to promote math, science and technology education by nurturing the enthusiasm of young people in these areas. To this end the TableSat team provided show and tell presentations, which encouraged kids to ask questions and open their minds to the concepts of attitude and control. This presentation included a demonstration of the TableSat, which is a visualization and training tool for the introduction of spacecraft sensors, actuators, and attitude dynamics. This interactive demonstration attracted many curious minds and provided a mechanism for exposing kids to the relevant concepts of attitude control.

Project Support

At the core of the FDAB is our support of flight projects, whether it is a mission to low-Earth orbit designed to study the climate, our own sun, or to explore the depths of the universe.

Aeronomy of Ice in the Mesosphere (AIM)
(POC: Peiman Maghami, Peiman.G.Maghami@nasa.gov)

AIM is a two-year mission to study Polar Mesospheric Clouds (PMCs), the Earth's highest clouds, which form an icy membrane 50 miles above the surface at the edge of space. The primary goal of the AIM mission is to explain why PMCs form in the first place and to explain their behavior. The AIM satellite has three instruments on board: CIPS, SOFIE and CDE. The SOFIE instrument, which measures the temperature and composition of the mesosphere and tells scientists about the chemistry and movement of air, had its scan mirror assembly damaged during testing in June of 2006. The only feasible replacement was a fixed mirror which required the mission to rely on the spacecraft to perform the duties of the scan mirror. FDAB was asked to assess the ability of the spacecraft attitude control system (ACS) to meet pointing and jitter requirements for a SOPHIE instrument with a fixed mirror. Guidance and analysis that was provided to the project resulted in a complete review of existing pointing requirements, identification of inconsistencies and deficiencies, a modification of current requirements, and the addition of new ones. The updated and improved pointing analysis indicated that all pointing requirements can be met with the fixed mirror configuration.

<u>Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation (CALIPSO)</u>
(POC: Michael Mesarch: Michael.A.Mesarch@nasa.gov)

On April 28, 2006, the Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation (CALIPSO) satellite was launched as part of a dual payload delivery with the CloudSat mission by a Delta-II 2420 expendable launch vehicle. CALIPSO, which uses an active LIDAR to study thin clouds and aerosols over the Earth, is part of the Earth Observing System's Afternoon Constellation (A-train) of satellites flying in formation in Sun-synchronous, polar orbits (Figure 1). The primary responsibility for operating the spacecraft and designing the maneuvers to insert CALIPSO into the constellation were undertaken by mission partners from CNES, who were also responsible for coordinating the maneuvers between CALIPSO, CloudSat, and the rest of the constellation to ensure the safety of all spacecraft. The flight dynamics support of CALIPSO was primarily a consultative effort provided by Laurie Mann of a.i. solutions, which was key in maintaining proper communications between NASA LaRC, CNES and JPL (responsible for CloudSat) during Launch and Early Orbit. In the end, CALIPSO executed its two orbit raising maneuvers, inserted itself successfully into the Afternoon Constellation, and subsequently performed inclination maneuvers in order to maintain its formation with Aqua.

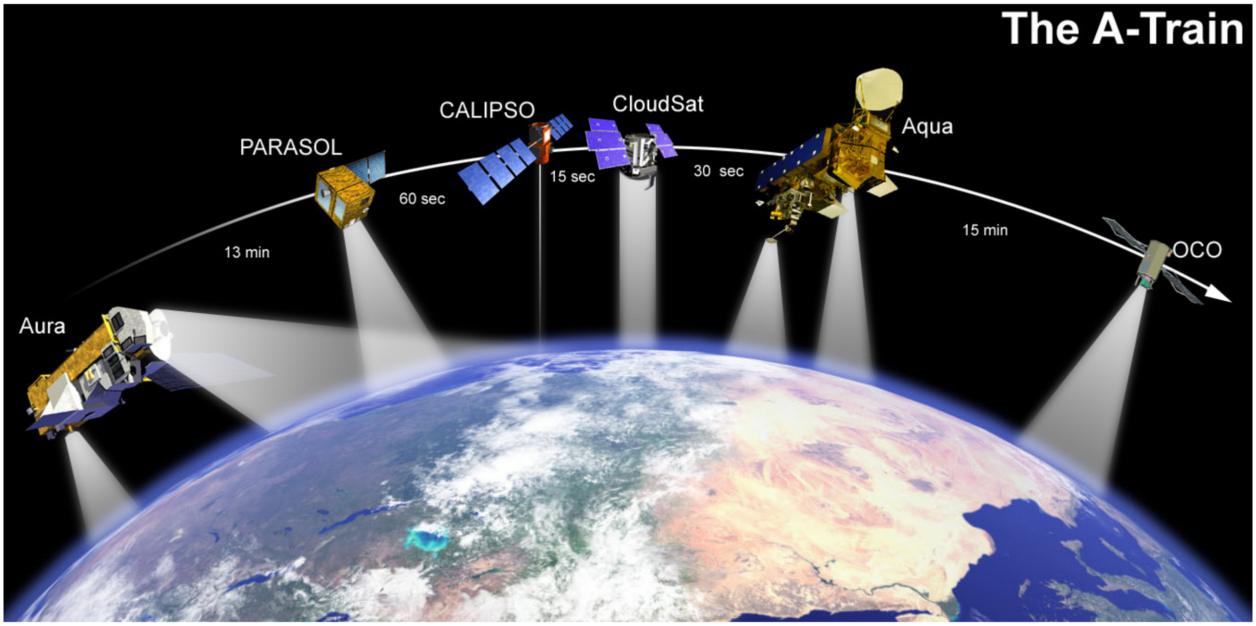

Figure 1: The Afternoon Constellation "A-Train" satellites, showing CALIPSO and the EOS satellites Aqua and Aura

Earth Observing System (EOS)
(POC: Dave Tracewell, David.A.Tracewell@nasa.gov)

FDAB has a lead role in managing the EOS spacecraft Aqua and Aura and the Earth Sciences Afternoon Constellation (or A-Train), which is comprise of Aqua, CloudSat, CALIPSO, PARASOL, and Aura (see Figure 1). Each of the spacecraft requires period drag makeup maneuvers and inclination adjusts in order to fly in formation in their specified sun-synchronous, repeat ground track orbit and daily screening of the threat of collision due to other spacecraft and debris. FDAB's efforts include planning, execution, reconstruction, and calibration of all the maneuvers performed by Aqua and Aura, the coordination of those activities with other members of the constellation, and the development and application of methods to assess to the risk of collision.

In order to maintain the coordinated science instrument viewing requirements within the A-Train, FDAB obtained an agreement across constellation for all members to perform their inclination adjusts in conjunction with Aqua. This coordinated series was begun in the Fall of 2006 but was terminated early because of unexpected performance in the Aqua inclination adjust maneuvers, that could have led to violation of mission ground track constraints. Aqua's inclination maneuver performance was analyzed by the flight dynamics team led by David McKinley of a.i. solutions. McKinley found that the discrepancy between the maneuver planning process and the actual maneuver performance was due to substantially less drag. The team then developed a Monte Carlo simulation to model the expected errors in the spacecraft propulsion and attitude control systems. The simulation results showed that with the level of drag, there was a 40% chance of achieving a positive SMA change at the attitudes flown and based on these results an approach to compensate for the performance was devised and a Spring 2007 inclination maneuver series was planned and coordinated to accomplish the desired inclination goals for the Constellation.

Conjunction Assessment (CA) analysis is routinely performed (daily) and is also performed prior to all planned Constellation maneuvers through an evolving task managed by the FDAB. CA analysis is critical to protect these multi-billion dollar Constellation assets from collisions between members and also from tracked debris and will soon be required based on interpretation of the draft NASA NPG 8715. A Constellation Coordination System (CCS) was also developed and enhanced in a joint effort between the FDAB and the Mission Applications Branch (MAB). It is utilized as a centralized receipt, conversion, distribution and analysis system to facilitate communication and exchange of products between Constellation members, especially during coordinated maneuvers.

Schatten Solar Flux Predictions
(POC: Bo Naasz: Bo.J.Naasz@nasa.gov)

The FDAB provides a number of services that require long-term prediction of solar activity in order to obtain accurate, long-term prediction of satellite orbits, and orbit decay rates in low altitude orbits. In particular, FDAB analysts and GSFC solar physicists, continue to use the solar flux predictions provided by Dr. Kenneth Schatten's models. Dr. Schatten employs a physically based method, know as a solar precursor method, to predict the mean solar flux for the upcoming solar cycle. This method uses direct and indirect measurements of the sun's polar magnetic fields near the minimum of the 11-year solar flux cycle, and solar dynamo theory to estimate the solar activity during the remainder of the cycle. Analysis over the past year has also identified a need for improved understanding of the effects of short-term solar flux variations on satellite orbit decay rates. To this end, FDAB has supported scientific analysis to incorporate physical phenomena of the sun and known characteristics of solar activity to develop a model of the short-term variations in solar flux. These models enable FDAB analysts to perform extensive (Monte-Carlo) satellite orbit decay analyses with a statistical set of solar flux profiles, and to determine the sensitivity of spacecraft orbit decay to short term solar flux variations.

Gamma-Ray Large Area Space Telescope (GLAST)
(POC: Mark Woodard, Mark.A.Woodard@nasa.gov)

The Gamma-Ray Large Area Space Telescope (GLAST) will provide full-sky surveys of the gamma ray field and make detailed observations of gamma ray burst events. GLAST will fly a redundant pair of VICEROY SGPS receivers to provide 1 PPS position, velocity, and time for spacecraft navigation. Flight dynamics support for GLAST will be primarily supported from the MOC, which will host an FDAB-provided attitude determination system (ADS) in the ground support software. The MOC will also use an extensive suite of Satellite Tool Kit (STK) modules to provide orbit prediction and mission planning support. Of particular note is the use of the STK Orbit Determination Tool Kit (ODTK) that will take telemetered GPS point-solutions and apply improved force models and filter/smoothing algorithms in order to increase the fidelity of the orbit solutions and enable accurate long-term orbit propagation. FDAB personnel tested ODTK using on-orbit GPS point-solutions from the QUIKScat satellite. The filter/smoothing algorithms improved the accuracy of the long-term orbit predictions by roughly two orders of magnitude.

FDAB personnel provided support of launch vehicle requirements. A Mission Integration Working Group (MIWG) meeting was held in September 2006 where KSC/Boeing presented the results of the Preliminary Mission Analysis (PMA). FDAB verified that the Monte Carlo analysis provided a GLAST separation vector that met all trajectory requirements. FDAB provided inputs for the Detailed Trajectory Objectives (DTO) analysis that is scheduled for completion at L-26 weeks (currently April 2007). The DTO will analyze a 20 week launch period (October 7, 2007 to February 23, 2008) with a total daily available launch window of approximately four hours, based on Sun lighting constraints. FDAB personnel provided GLAST SAA analysis, GLAST orbital decay predictions over both 5 years and 10 years using the latest Schatten predictions, and GPS receiver data analysis. FDAB provided the FOT Mission Planning Team with a GLAST 30-day launch ephemeris based on the separation vector provided by KSC. A GLAST Flight Dynamics Peer Review was held in September 2006 and 12 RFAs were received. Testing of the ADS was started and is continuing. The ability of FDF to received Differenced One-Way Doppler (DOWD) data was successfully demonstrated during CTV testing.

James Webb Space Telescope (JWST)
(POC: Conrad Schiff, Conrad.Schiff-1@nasa.gov)

The JWST is a large, infrared-optimized space telescope scheduled for launch to the Sun-Earth L2 libration point in 2013. The FDAB is providing all mission design, maneuver planning and orbit determination support for the JWST.

In 2006, the flight dynamics team participated in the Momentum Management Working Group (MMWG) to address momentum buildup due to the large sunshield and its effects on orbit determination and stationkeeping. The MMWG team consisted of GSFC, Northrop Grumman Space Technology (NGST) and the Space Telescope Science Institute (STScI). As part of the mitigation strategy, the flight dynamics team developed unique algorithms that optimize stationkeeping fuel costs and optimize the direction of the delta-V perturbation due to momentum unload maneuvers.

The flight dynamics team also presented an Orbit Determination Peer Review to a select panel made up of industry, academic and government experts. The panel confirmed the orbit determination operations concept for JWST and proposed the next steps to support a Mission Preliminary Design Review.

Lunar CRater Observation and Sensing Satellite (LCROSS)
(POC: Steve Cooley, D.S.Cooley@nasa.gov)

The FDAB began providing flight dynamics support for the ARC-managed LCROSS mission during 2006. LCROSS is a secondary payload, co-manifested with the GSFC-managed Lunar Reconnaissance Orbiter (LRO) mission, scheduled for launch on October 28, 2008 on an Atlas V launch vehicle (LV).

The purpose of the LCROSS mission is to search for water-ice on the lunar surface. LCROSS has a unique design in that it carries the spent upper stage of the LV, called the Earth Departure Upper Stage (EDUS), with it for most of its trajectory. LCROSS, with the EDUS still attached, will perform a lunar swingby, go into a high ecliptic inclination orbit about the Earth for 3-4 orbit periods, and then impact the lunar south pole. Eight hours before impact, EDUS and LCROSS will separate. The EDUS will than impact the lunar south pole while several LCROSS instruments, as well as selected ground assets, will analyze the impact plume for signs of water-ice. LCROSS, itself, still in view of the ground assets, will then also impact the moon.

The FDAB helped ARC develop the baseline mission concept utilizing a northern hemisphere lunar swingby, followed by a 3½ month cruise orbit before impacting Shackleton crater near the lunar south pole.

Solar Terrestrial Relations Observatory (STEREO)
(POC: Michael Mesarch, Michael.A.Mesarch@nasa.gov)

The twin Solar Terrestrial Relations Observatory (STEREO) spacecraft were launched on October 25, 2006 at 8:52 PM EDT. The Delta-II 2925 expendable launch vehicle provided a good ride to the STEREO spacecraft, inserting them into their highly eccentric phasing orbit with apogee out past lunar distance (Figure 2). From the phasing loops, the STEREO spacecraft were maneuvered to target lunar gravity assists to place the spacecraft into their mission orbits – leading and lagging heliocentric drift-away orbits (Figure 3).

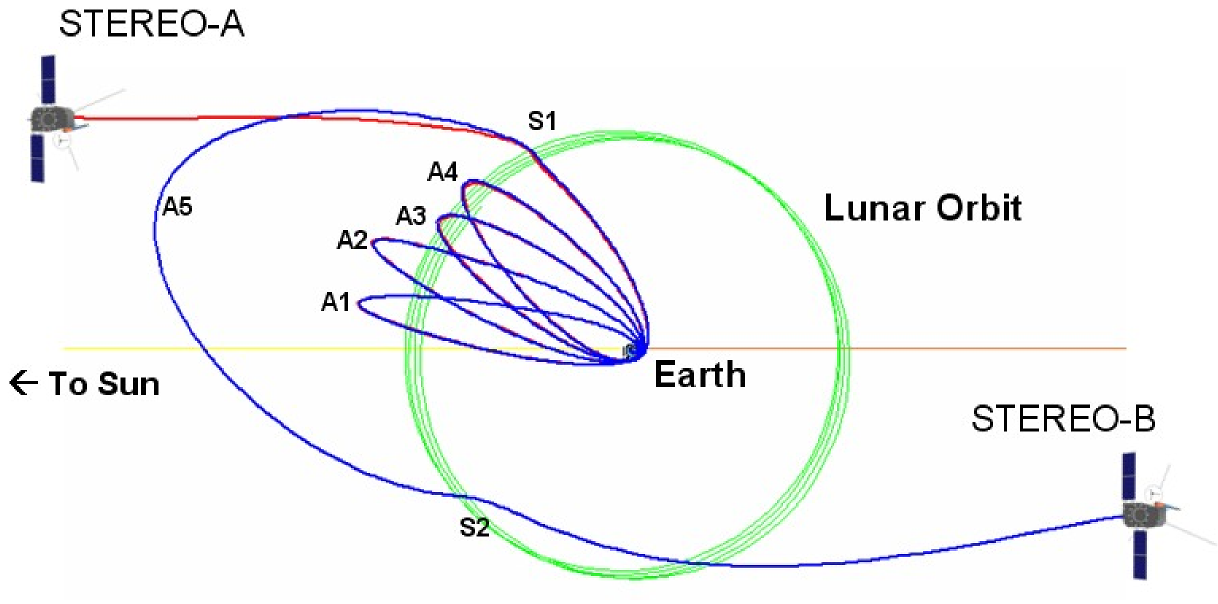

Figure 2: STEREO Phasing Loops (Sun-Earth Rotating Coordinates)

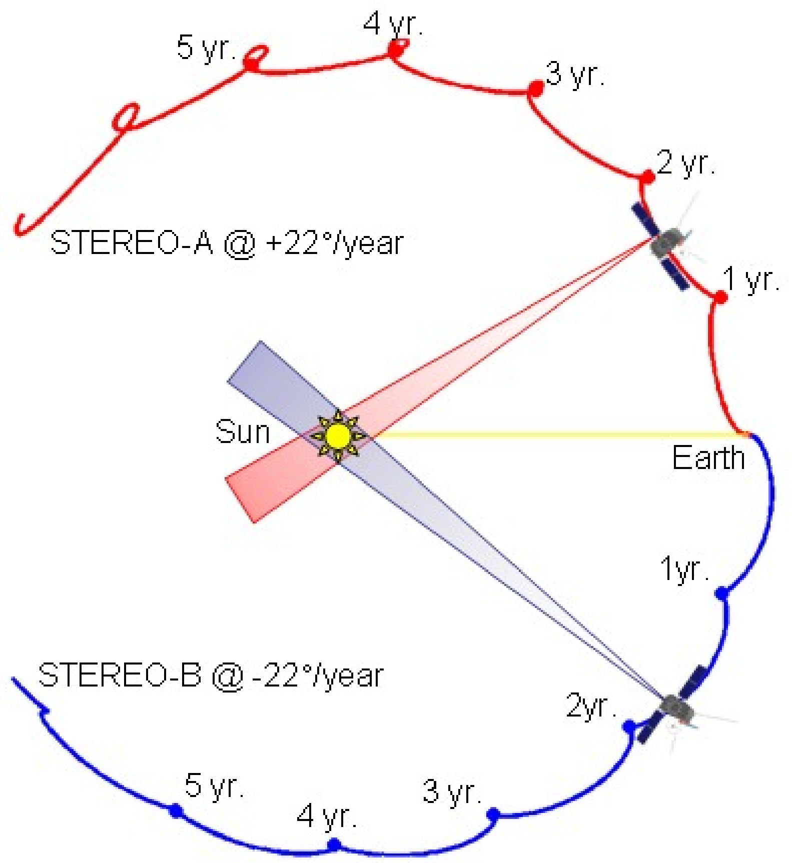

Figure 3: STEREO Drift-Away Orbits (Sun-Earth Rotating Coordinates)

The STEREO Flight Dynamics Navigation Team was responsible for collecting tracking data (range and Doppler), processing the data using the Goddard Trajectory Determination System (GTDS), and providing the orbit solution to both the Applied Physics Lab (APL) for trajectory design updates and to the Deep Space Network for spacecraft acquisition. Updates to GTDS had been performed so that GTDS could process the ramped, X-band range and Doppler data needed for the STEREO mission. The updates proved successful as the excellent support allowed the APL mission design team to target four maneuvers for STEREO-A prior to its lunar gravity assist and six maneuvers for STEREO-B for its two lunar gravity assists. The lunar gravity assists were performed flawlessly allowing the STEREO spacecraft to achieve its ± 22 °/year heliocentric drift rate to within 0.35 °/year for STEREO-A and 0.001 °/year for STEREO-B. Furthermore, the orbit solutions were sufficiently accurate to target and fine tune a lunar transit of the Sun on February 25, 2007 as seen through STEREO-B's SECCHI instrument following its final lunar gravity assist.

Space Technology 7 Disturbance Reduction System (ST7-DRS) Dynamic Control System
(POC: James O'Donnell, James.R.ODonnell@nasa.gov)

The Space Technology 7 Disturbance Reduction System (ST7-DRS) is a project within the New Millennium Program with a mission objective to test advanced colloidal micronewton thrusters (CMNT) and the algorithms needed to use those thrusters to achieve drag-free flight. ST7-DRS is scheduled to fly in 2010 as an instrument package aboard the ESA LISA Pathfinder spacecraft. Technical objectives of this mission include using the CMNTs, an ESA provided drag-free sensor (DFS), and algorithms and flight software being developed by FDAB to validate that a test mass follows a purely gravitational trajectory within $3\times10^{-14}(1+(f/3\ \text{mHz})^2)\ \text{m/s}^2/\sqrt{\text{Hz}}$, and controlling spacecraft position to an accuracy of less than 10 nm/$\sqrt{\text{Hz}}$ within a 1–30 mHz measurement band. The ST7-DRS mission is a partnership consisting of JPL, the Busek Co., and GSFC. The responsibilities of the FDAB to the project include the development of the Dynamic Control System (DCS) that controls the spacecraft position and attitude to establish drag-free motion of the test masses within the DFS, development of a full nonlinear dynamic model of the spacecraft and test masses, and generation of flight software implementing the DCS algorithms.

This was an active year for DCS. At the end of 2005, a domestic drag-free sensor being developed by Stanford was descoped from the mission, resulting in the need to use the ESA DFS to close the control loop. As a result, the DCS team needed to analyze, design, implement in flight software, and test DFS control algorithms (which had been the responsibility of Stanford before the descope). The DCS team held a successful Critical Design Review in February 2006 and made an initial delivery of the new algorithms and flight software in June. Final acceptance testing of the new flight software continued throughout the rest of the year. As 2006 closed, the DCS team was conducting their final redesign, based on updated DFS and spacecraft parameters, and preparing their final software delivery to the project at JPL. In addition to development of the DCS control algorithms and flight software, the DCS team supported the project system-level testing and meetings with ESA representatives, and developed a "phenomenological" CMNT model that could be provided to ESA and their contractors for development of their control algorithms without revealing any ITAR-controlled or intellectual property information.

Future Mission Concept Development

FDAB has been instrumental in developing new algorithms, techniques, and technologies that allow future mission to become a reality. The articles below give a sampling to these efforts.

Advanced Attitude Determination and Sensor Calibration
(POC: Rick Harman, Richard.R.Harman@nasa.gov)

The purpose of the advanced attitude determination and sensor calibration task is to improve the accuracy and efficiency of both processes taking in account current and future mission requirements as well as to disseminate the analysis and provide consultation. Coarse Sun Sensors (CSSs) are standard backup sensors on most missions due to their simplicity and low cost. Spacecraft designers are fairly creative on placement of these sensors which is a challenge for maintaining a multi-mission attitude determination system. A new method of processing CSS data using fuzzy cones has been developed which provides a generalized method for dealing with sun angles from multiple CSSs and deriving a spacecraft to sun vector in body coordinates. Figure 3 is an example of the relative probabilities of data from three CSSs. This algorithm is in the process of being added to our operational multi-mission attitude determination system.

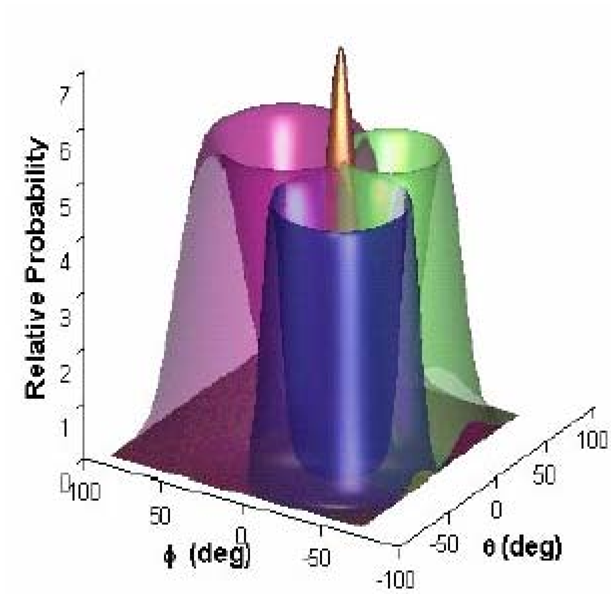

Figure 4: Simulated Relative Probability of Sun Direction Using Three CSS

The second goal of the advanced attitude determination task is to improve the calibration accuracy of spacecraft sensors. A new magnetometer calibration algorithm was developed for spinning spacecraft. This iterative calibration algorithm uses the Shuster Two-Step attitude independent magnetometer algorithm as a first-cut on the magnetometer calibration, then executes the Markley Variable Filter to estimate the spacecraft attitude, followed by executing our alignment calibration utility. This process is iterated until it converges. This algorithm was successfully used for the Space Technology (ST)-5 mission and is part of our multi-mission operational attitude determination and sensor calibration system. Figures 2(a) and 2(b) provide examples of the usefulness of this algorithm using ST-5 flight data.

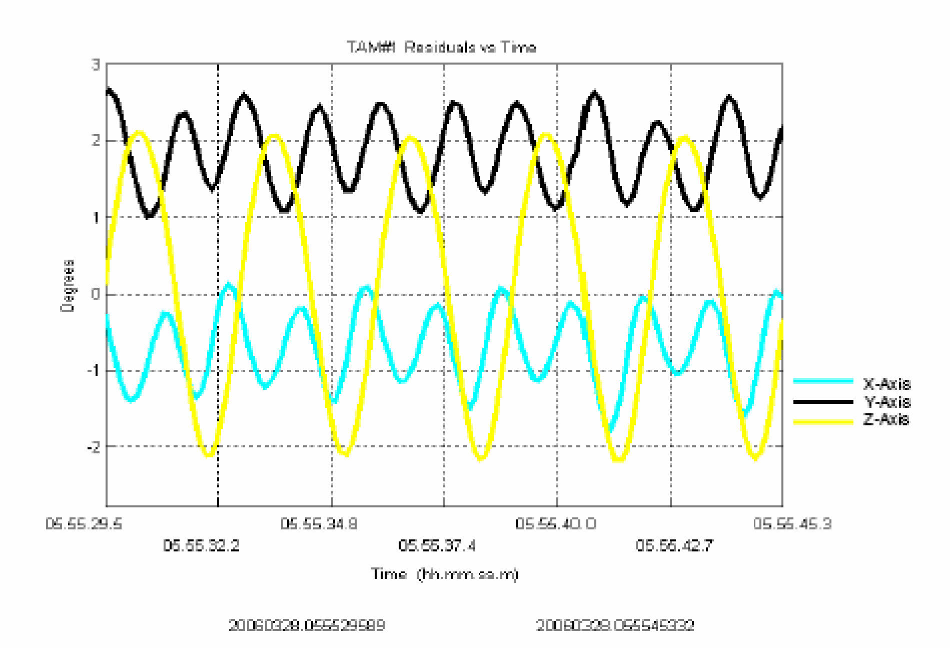

Figure 5: ST-5 Pre-Calibration Magnetometer Residuals

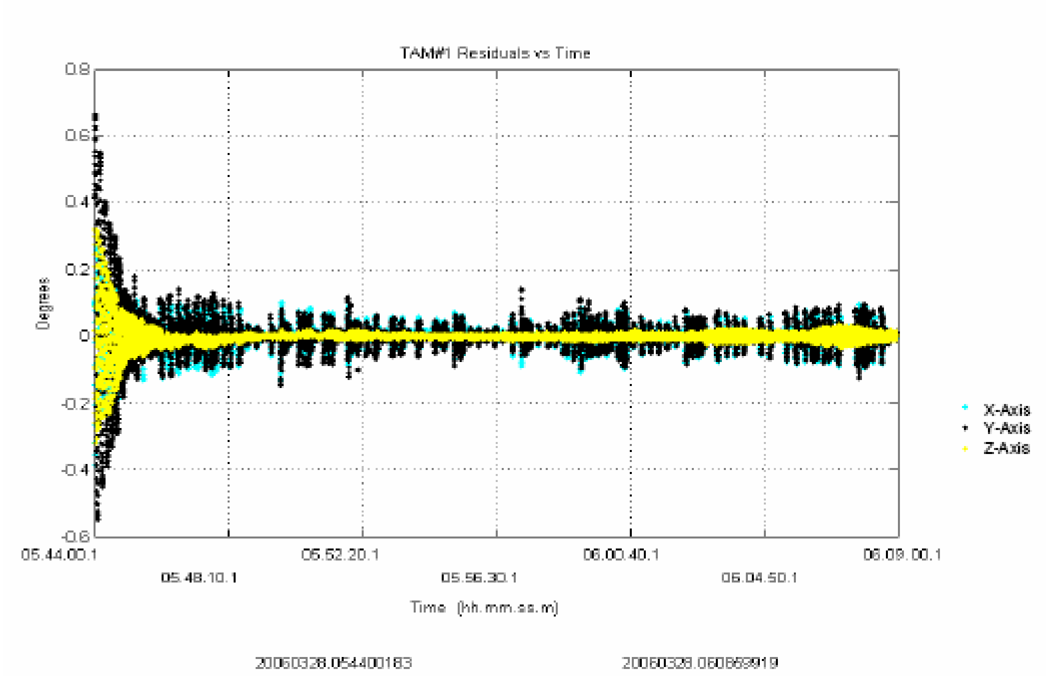

Figure 6: ST-5 Post-Calibration Magnetometer Residuals

The third goal of this task is to improve the overall process efficiency of ground attitude estimation and sensor calibration. To this end, the ST-5 attitude system was automated to ingest telemetry, compute spacecraft attitudes, provide QA checks on those attitude solutions, and deliver the attitude data and adjusted sun sensor time-tags to the ST-5 scientist.

Lastly, this task has disseminated various written various technical reports on spacecraft attitude estimation and sensor performance as well as consultation. In particular, the task published the following papers: "Spinning Spacecraft Attitude Estimation Using Markley Variables: Filter Implementation and Results", "Attitude-Independent Magnetometer Calibration for Spin-Stabilized Spacecraft", "Attitude Sensor Pseudonoise", "Iterative Magnetometer Calibration", "Accommodating Sensor Uncertainty in the Cones Method: Polycones and Fuzzycones", and an updated version of the "Spacecraft Attitude Determination Accuracy from Mission Experience." The task also provided consultation to a variety of current and future missions.

Integrated Mission Design Center (IMDC)
(POC: Dave Olney, David.J.Olney@nasa.gov)

As it has in the past, the FDAB orbit and attitude group provided study-support to the Goddard Integrated Mission Design Center (IMDC). The IMDC provides intense, rapid, engineering studies for a wide range of future missions. This past year, missions studied in the IMDC included a Mars Observer, a Lunar Communications satellite, a pair of spacecraft exploring the radiation belts, a mission incorporating a large constellation of satellites controlled to determined to accuracies that a very large telescope optical train, and a series of missions intended to support Earth science wind, ice, forest, and ocean surveys and monitoring. A partial list of the missions support in 2006 are: MAVEN, NOW, MPILE, MOLSAM, ST9-SS4, RBSP, SST, MGrace, LunarComm, MOO, GeoMac, Ceic, LeoMac, VegBio, GWOS, GeoMDI, Oceans

Relative Navigation Sensor Effort
(POC: Chip Campbell, Charles.E.Campbell@nasa.gov)

The Relative Navigation Sensor effort, to establish simulation tools for sensor and pose technologies, has supported Natural Feature Image Recognition with implementation of Long Quan and Zhongdan Lan's "Linear N-Point Camera Pose Determination". The algorithm supports pose acquisition. Closed form forward and inverse kinematics and code for Shuttle Arm simulation have been tested for over one million poses.

Similarly, the forward and inverse kinematics algorithms for the camera pose system has been developed and implemented. Freespace's console supports a Matlab-like language which appears to be functioning well; it includes a shared-memory memory allocator library, singular value decomposition, eigenvalues, units, cell arrays, multiple platforms (Linux, MacOSX, SGI), online help, and many other capabilities.

Solar Sail Proposal for the Space Technology (ST – 9) Mission
(POC: Dave Mangus, David.J.Mangus@nasa.gov)

After years of light weight sail material construction and deployment ground testing under the MSFC In-Space Propulsion (ISP) Program, GSFC took over the lead to develop a systems level approach that would fit within the budget constraints of an ST-9 mission. For 3 years, the FDAB GN&C built a strong working relationship with MSFC, LARC, JPL, Ball Aerospace, L'Garde, and Orbital, leading the effort in developing innovative ways to control the gossamer structure in a low Earth orbit. A 6 AM/PM Sun synchronous orbit was selected to maximize Sun time. By rotating the sail at orbit rate, holding a boom toward Nadir, and setting a fixed sail to Sun line angle, thrust is produced in a very low gravity gradient environment. The FDAB also worked closely with JPL in developing innovative methods for backing out the low thrust magnitude and direction produced by solar pressure from flight data.

Space Technology 9 (ST9) Precision Formation Flying
(POC: Bo Naasz, Bo.J.Naasz@nasa.gov)

The FDAB participated in development of the ST9 Precision Formation Flying (PFF) mission concept. PFF is defined as the continuous, closed-loop, precise control of the relative motion of multiple spacecraft geometry, implemented through a crosslink. The ST9 PFF mission will advance PFF to the point where it can be inserted into future operational NASA science missions, opening a new avenue for high angular resolution imaging, observation, and astronomy.

PFF comprises algorithms, software, methodologies, systems engineering, and hardware. The challenge in mission design is to validate as many of the elements above with the greatest scalability and applicability to future missions as can be incorporated into a highly-cost-constrained space mission. ST9 PFF is the only complete mission concept under consideration for flight prior to the planned NASA strategic PFF-enabled mission concepts, namely the Terrestrial Planet Finder-Interferometer (TPF-I), Stellar Imager (SI), Black Hole Imager (BHI), Life Finder (LF), and Planet Imager (PI).

FDAB engineers played vital roles in the ST9 PFF team, providing expertise in such areas as formation mission design, onboard navigation and control, formation sensor design and selection, spacecraft propulsion system design, attitude determination and control system design, and inter-satellite and satellite-ground communication system design. We also performed extensive testing in the GSFC Formation Flying Test Bed (FFTB) to bring PFF algorithms to Technology Readiness Level 4.

Laser Interferometer Space Antenna (LISA)
(POC: Peiman Maghami, Peiman.G.Maghami@nasa.gov)

Unlike typical observatories, which detect electromagnetic waves traveling through space-time, the Laser Interferometer Space Antenna (LISA) will detect ripples in space-time itself. Science targets include galactic binaries, merging supermassive black holes, intermediate-mass/seed black holes, and cosmological backgrounds. Gravity waves are detected by measuring the strain in space, i.e. the change in distance between a set of masses (test masses or proof masses) separated by a great distance. LISA uses laser interferometeric measurement of the change in distance between test masses. Each of the three LISA spacecraft embodies two test masses. Space allows very long arm lengths (5 million km for LISA) and a very quiet acceleration environment (3.5×10^{-15} m/s^2/Hz^{½} for LISA), which allows for the detection of gravity wave strains to a best sensitivity of 3×10^{-24} strain/Hz^{½} over the measurement band of 10^{-4} to 10^{-1} Hz for a one-year observation. Stringent requirements are placed on the rotational and translational dynamics of each spacecraft to ensure that the proper sensitivity for science measurements can be achieved. The LISA mission was supported in a number of areas: implementation of the strap-down baseline; micronewton thruster configuration; test mass charge management system; initial acquisition strategies; and GN&C hardware selection.

A new strap-down baseline was adopted by the mission, in which optical measurements of the position and attitude of test masses in three degrees of freedom replaced capacitive sensing in order to reduce residual acceleration noise along the sensitive axis of the test mass. Furthermore, a single-axis actuated mirror was introduced to provide in-plane compensation for the point-ahead angle. This relieved the test mass control system from tilting the test mass for point-ahead compensation. The disturbance reduction control system and its five control systems were redesigned to accommodate the strap-down baseline, and to incorporate updated hardware models from the LISA Pathfinder. A baseline configuration for the optimal number and orientation of micronewton thrusters was developed. A 6+6 thruster layout has been chosen to minimize the overall mass of the propulsion system and provide full redundancy. The optimal orientation of the thrusters was determined, using a minimax approach, to maximize the minimum thrust bias under minimum loading conditions. On-orbit charge management of test masses was also investigated. A continuous charge control system was designed, and shown to be quite effective in reducing the state of charge of the test masses at the lower end of the LISA band, where it is most critical.

Origins Spectral Interpretation Resource Identification Security (OSIRIS)
(POC: Russell Carpenter, James.R.Carpenter@nasa.gov)

The FDAB will perform all navigation functions for the Origins Spectral Interpretation Resource Identification Security (OSIRIS) Mission. FDAB has assembled a preeminent team with unmatched expertise and relevant mission experience, most notably from the NEAR and Hayabusa missions. On these missions, key members of our team, Dr. Bobby Williams of KinetX and Dr. Robert Gaskell of Planetary Science Institute (PSI), have already closely collaborated with the navigation experts on the OSIRIS science team to generate all of the products described in the OSIRIS SOW. Dave Rowlands of the GSFC Planetary Geodynamics Laboratory will lead a group consisting of himself, Dr. Frank Lemoine, and Dr. Greg Neumann, in developing gravity field models in support of the navigation team, as they have done for the NEAR mission. Lee Bryant of JSC¹s Flight Mechanics and Trajectory Analysis Branch, with extensive experience with Earth and planetary entry analysis, will provide a backup re-entry analysis and operational support capability.

The GSFC Flight Dynamics Facility (FDF) will be the source for all navigation products. During early orbit, inbound and outbound cruise phases, and Earth approach phases, FDF personnel will generate all routine orbit determination and maneuver products using our existing suite of operational tools and procedures that have successfully navigated all GSFC near Earth and deep space missions for the past 40 years. As a crosscheck, KinetX will generate comparison solutions to validate the FDF products, on a periodic basis for routine operations and for all mission critical events.

These crosscheck solutions will incorporate techniques such as Delta-Differenced One-Way Range, attitude-dependent multi-surface solar radiation pressure models, etc. as the circumstances dictate. As OSIRIS approaches the asteroid 1999 RQ36, KinetX will relocate to the FDF, and GSFC personnel will hand off to KinetX the primary OD role. GSFC personnel will then take over the backup-crosschecking role previously held by KinetX. The handover point will be the asteroid capture maneuver. As imaging and LIDAR data become available, GSFC¹s Planetary Geodynamics Laboratory, and the Planetary Science Institute will begin to update the shape, spin, and gravity models of the asteroid, in preparation for the orbital, fly-by, and touch and go phases. This handover process will reverse for the asteroid departure. Leading up to the Earth approach and re-entry, the navigation team will work closely with NASA LaRC personnel that have already been selected by OSIRIS to ensure a safe sample re-entry to the Utah Test and Training Range. JSC's Flight Mechanics and Trajectory Analysis Branch will provide re-entry simulation and footprint analysis products as a backup crosscheck to the LaRC products.

Vesper

(POC: Greg Marr, Gregory.C.Marr@nasa.gov)

The FDAB supported the pre-phase A and phase A Vesper Discovery proposal efforts. The FDAB led the mission design and mission analysis efforts. Vesper is a Venus orbiter. Vesper will nominally launch in late 2012 and will be placed in an eccentric, polar Venus orbit after a Venus flyby. The maximum launch C3 (twice the launch energy per unit mass) is 12.1 km^2/s^2 for the nominal 20 day launch window in late 2012. The Earth-to-Venus transfer lasts approximately 24 months (approximately 2.5 heliocentric orbits), and Venus orbit insertion occurs approximately 3.5 months after the Venus flyby. Venus orbit insertion after a Venus flyby results in a polar approach that allows flexibility in orienting the polar mapping orbit, achieves a specific southern hemisphere periapsis declination (which is desirable for science), and minimizes shadow duration. The pre-phase A mission analysis and the phase A mission analysis, which is ongoing at this writing, includes spacecraft delta v analysis and navigation analysis. Backup launch windows in late 2013 and late 2014 have been determined.

Space Technology 5 Launch and Operations

(POC: James O'Donnell, James.R.ODonnell@nasa.gov)

Introduction

On March 22, 2006, the three Space Technology 5 spacecraft were launched into orbit atop a Pegasus launch vehicle. The preparation and launch and operations support of this in-house technology demonstration mission was a major activity of the Flight Dynamics Analysis Branch (FDAB). The Space Technology 5 (ST5) mission was part of the NASA New Millennium Program (NMP), which validates technologies for future science programs. The purpose of ST5 was to validate the ability to design and manufacture multiple small spacecraft and operate these spacecraft as a system. Results from ST5 will be used to design future missions using constellations of spacecraft such as the Magnetospheric MultiScale (MMS) mission currently under development. The NMP technologies that ST5 validated were a miniature communications transponder, a cold gas micro-thruster, variable emittance coatings, CMOS ultra-low power radiation tolerant logic, and a low voltage power subsystem. Other new technologies and hardware flying on the ST5 spacecraft included a miniature science-grade magnetometer, a miniature spinning sun sensor, the spacecraft deployment mechanism, the magnetometer deployment boom, an in-house designed passive nutation damper, and an X-band antenna.

ST5 Mission Overview

Figure 7 shows one of the ST5 spacecraft with its magnetometer boom in the stowed position (the structure on the left of the spacecraft is part of the Pegasus Support Structure that holds the spacecraft within the launch vehicle) along with a schematic of spacecraft showing the important components and with the boom deployed. As is shown on the schematic, the body of the spacecraft is just over half a meter long; fully deployed, the magnetometer boom adds another three-quarters of a meter to the spacecraft's length. The three ST5 spacecraft were denoted spacecraft 094, 155, and 224, based on the transponder spacecraft identification numbers of each.

Figure 8 shows the three ST5 spacecraft as mounted in the Pegasus Support Structure (PSS). The spacecraft were meant to be deployed after third stage cutoff in the following order: the forward spacecraft (leftmost in figure) at third-stage cut-off (3SCO) + 200 seconds, the middle spacecraft at 3SCO + 390 seconds, and the aft spacecraft at 3SCO + 530 seconds. Even though the deployment order of the spacecraft was as shown in Figure 8, from left to right, because of the dynamics of the planned orbits and firing of the Pegasus attitude control thrusters, the expected rise order was sc155, sc224, and finally sc094.

Separation, Deployment, and Initial Acquisition

The three ST5 spacecraft launched successfully at 14:03:52.69 UTC on March 22, 2006. There had been some concern both about possible recontact between the three spacecraft and about our ability to acquire and track each spacecraft using their X-band tracking information. On launch day therefore, there was much relief in the control room when initial contact was made with each spacecraft as planned.

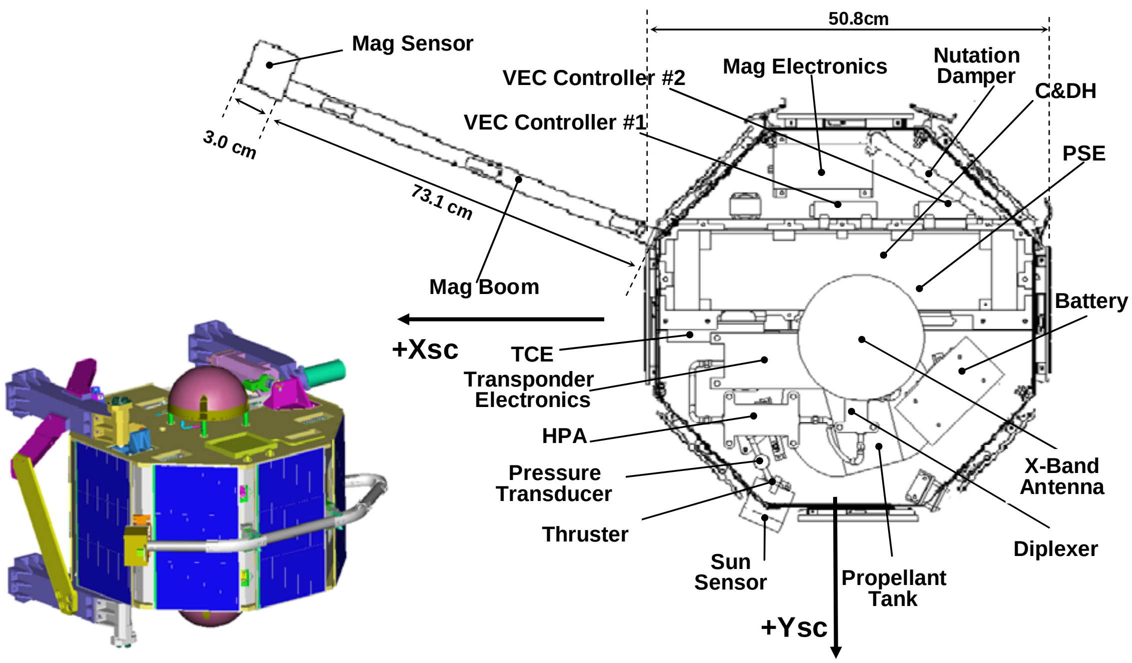

Figure 7: ST5 Spacecraft Schematic

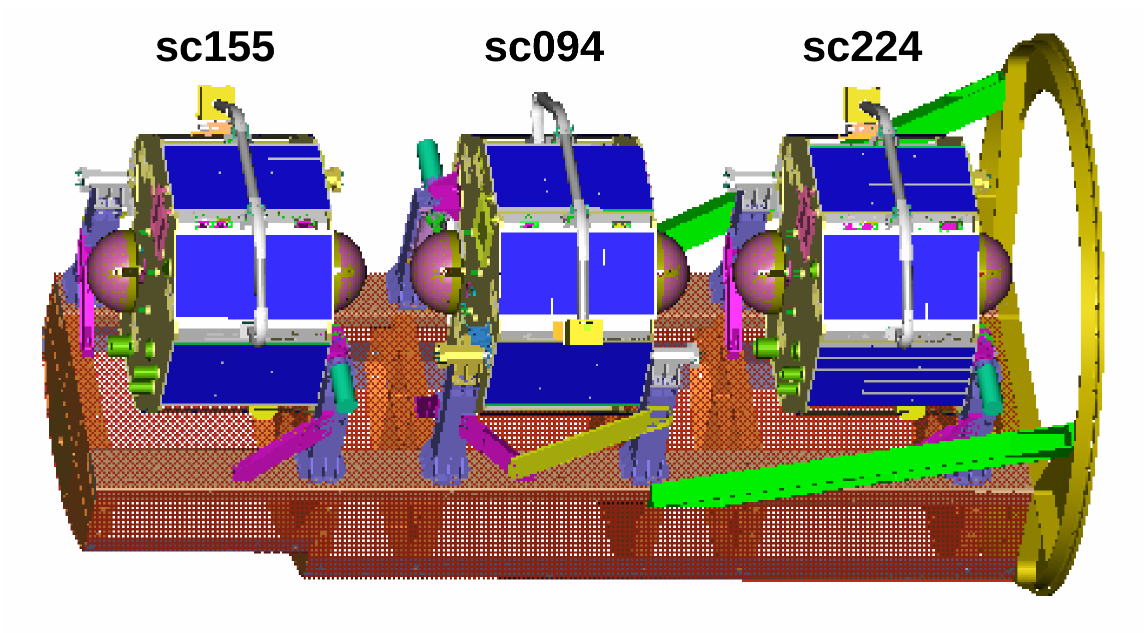

Figure 8: The Three ST5 Spacecraft in the Pegasus Support Structure

However, as each was contacted, it was obvious that an unexpected anomaly was affecting all three. The telemetry point showing the delta time between sun sensor pulses was alternating between a smaller and a larger value. Both of these values were smaller than the expected spin period, though the sum of the two was approximately equal to the expected spin period for each spacecraft. Additionally, there was a flood of downlinked "buffer overrun" event messages from each spacecraft.

In addition to the anomalous conditions apparent from downlinked telemetry, analysis of the launch vehicle separation vectors for the three spacecraft showed that the spacecraft deployment from the Pegasus third stage was completely out of bounds with what was expected, resulting in the forward spacecraft being significantly ahead of the other two and moving away from them at high velocity. The rise order was different than expected; sc155 was still in front, but sc094 was now the middle spacecraft and sc224 bringing up the rear. It was subsequently discovered that the Pegasus third stage had ended up within the ST5 constellation, between sc155 and sc094. In spite of all of this, however, there was no immediate danger to any of the spacecraft. The orbit rates of the three spacecraft left no fear of recontact, and while the sun sensor sun pulse telemetry was suspect, the elevation angles seemed to be accurate and were showing each spacecraft oriented as desired. Being spin-stabilized and power and thermal safe with no other time-critical operations, there was time to diagnose the anomalies.

Sun Sensor Spurious Pulses

Approximately four hours after the initial contact with the ST5 spacecraft, the "ST5 Anomaly Team" that had been set up before launch was activated. This team, along with members of the flight operations and flight support teams, began to assemble data and information to identify the cause of the anomaly. This process was somewhat complicated by the need to monitor the continued operation of each of the *three* spacecraft during each of the real-time contacts. However, because they were spin-stabilized and in a safe configuration, there was no urgency to prepare for time-critical operations.

Sun Sensor Spurious Pulse Characterization

The search for the cause of the sun sensor anomaly ended the day after launch. As a part of the initial fault tree generation on launch day, Adcole was informed of the spurious pulses anomaly that were seen. Without providing exact details on the timing of the pulses, by the next morning, Adcole reported back to the ST5 anomaly team that they had reproduced the spurious sun pulse effect. This was achieved through test on a spare MSSS Engineering Unit built for ST5. Adcole's results showed a spurious pulse occurred approximately 70° in the spin plan in advance of the true sun pulse, which was identical to the phenomenon being experienced on each spacecraft MSSS. The MSSS was designed to generate a Sun pulse output when the sun crossed through the command plane of the sensor, which is nominally perpendicular to the MSSS mounting surface.

Because the spurious pulses are approximately 70° in advance of the true Sun pulse, the signals triggered by the Sun correspond to the smaller Δ time. For sc224, there was "short" Δ time of ~0.5 sec and a "long" Δ time of ~2 sec, meaning that the sc224 spin period was ~2.5 sec. The elevation angle corresponding to the good pulses is approximately 0.7°. The elevation angle reported as a result of a spurious pulse is the result of whatever light happens to be illuminating the sun sensor at the time of the pulse. In subsequent testing at Adcole, they were able to produce data showing the elevation angles that would be reported from spurious pulses, depending on the true elevation of the spacecraft (see Figure 9). It should be noted that the elevation angle reported during spurious pulses was much more vulnerable to contamination by other light sources, particularly Earth albedo. There is one other "feature" of the sun sensor that would become important to dealing with the anomaly in actual operation. Occasionally during a spin period there was no spurious pulse. As a result, for that particular spin cycle, the Δ time reported was the actual spin period of the spacecraft.

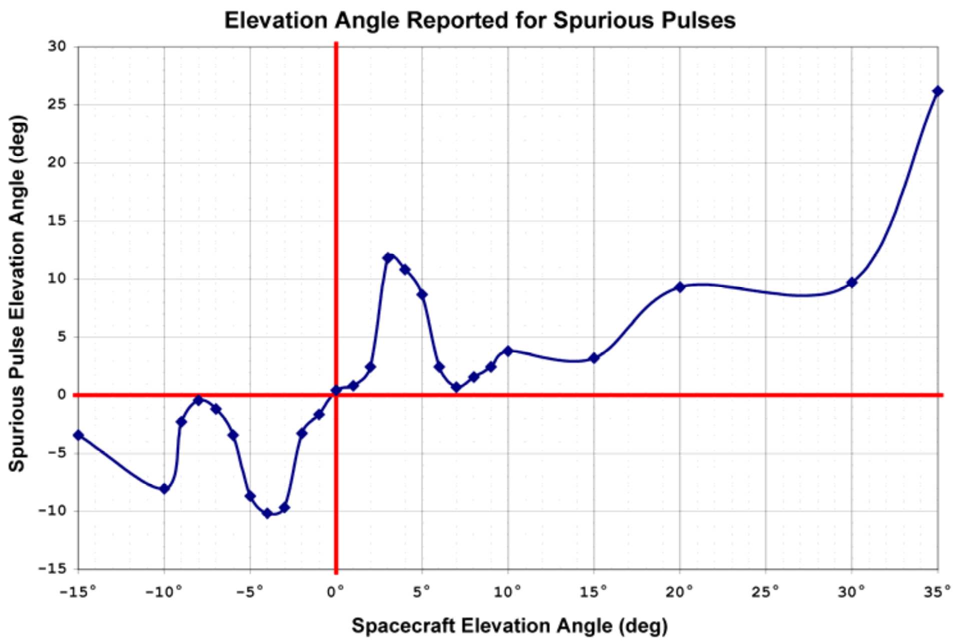

Figure 9: Elevation Angles from MSSS Spurious Pulses

Effects of Spurious Pulses on Spacecraft Operations

For each time the MSSS produced a pulse, whether a true Sun pulse or a spurious one, it triggered several actions on the spacecraft. Two of these actions, one in software and one in hardware, were of primary concern to the guidance, navigation, and control (GN&C) flight support and anomaly teams. On the software side, each sun pulse would trigger a software interrupt service routine (ISR) which would then start the flight software attitude control (AC) task. The AC task would then read the elevation angle of the spacecraft and calculate a filtered spin rate based on the Δ time since the last pulse. In the event that that the spacecraft had been commanded into its sun acquisition or attitude precession modes, the AC task would also calculate the timing and duration of the next cold gas thruster pulse. Note that the buffer overrun messages flooding the downlinked event messages were a result of the multiple, closely-spaced spurious pulses generated during most spin cycles. The hardware action triggered by the MSSS pulses is related to operation of the cold gas thruster. For sun acquisition and attitude precession mode, the timing of the thruster firing was based on receipt of the Sun pulse.

Of these two actions, the hardware-based action was the one that was the most problematic. The ISR routine that responds to MSSS pulses and the AC task that was used to implement the desired actions could be rewritten and patched on-orbit, if necessary. However, there was no way to change the hardware action related to thruster firings. When the spacecraft was placed in sun acquisition or attitude precession mode, it would calculate thruster firings as a delay and a pulse width and write those commands to the thruster hardware command registers. When the next MSSS pulse was received, whether it was a true Sun pulse or a spurious one, the thruster hardware would then wait out the commanded delay before firing the thruster for the desired pulse width. Note that this was not an issue for thruster firings associated with orbit maneuvers, as those were fired strictly on a separate 2 Hz clock. If another pulse was received during the delay time of a thruster command, processing of that command would stop in favor of the next one (if any).

The combination of these two actions results in a “keep-out” zone for thruster firings twice the size of the ~70° between the spurious pulse(s) and the true Sun pulse (see Figure 10). Any command generated at the time of the true Sun pulse would probably not be executed. The thruster hardware would attempt to execute it at the time of the first spurious pulse, but since there are usually multiple spurious pulses, the command would be stopped before it could actually fire. This eliminates the first half of the keep-out zone. However, because the number of spurious pulses varies, it is possible that such a command could be executed. To ensure that thruster commands occur when they are desired, it is necessary to use a minimum delay time corresponding to the amount of time between the spurious and true Sun pulse. This means there will be no undesired firing triggered by the spurious Sun pulse, but it doubles the size of the keep-out zone needed to get desired movement of the spacecraft spin axis. While this created a sizable zone during which thruster firings were not permissible, it did not create any absolute restrictions on moving the spacecraft spin axis, since it would be possible to orient the axis as desired using multiple maneuvers, if necessary.

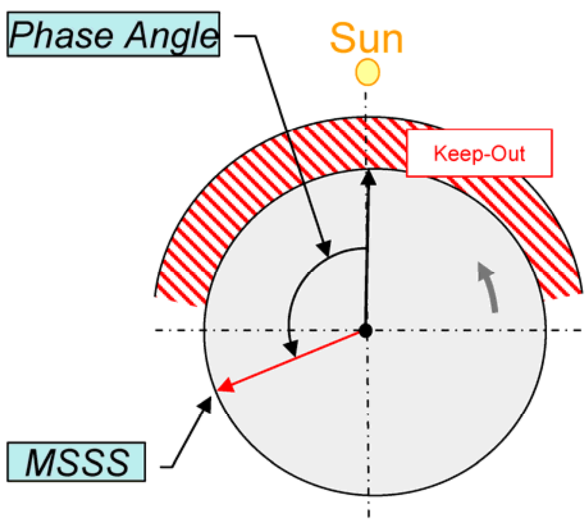

Figure 10: Attitude Precession Maneuver Restrictions Due to MSSS Anomaly

On-Orbit and Operational Tests and Mitigation

A number of on-orbit fixes were contemplated to deal with the spurious pulses, though only two were finally implemented. The first on-orbit fix that was implemented was designed to eliminate the flood of buffer overrun messages generated by the spurious pulses. While this did not change the functionality of the spacecraft, it did allow the event message buffer to become more useful since other messages being sent down from the spacecraft could be seen. The second on-orbit software change enacted was not implemented as a fix but was designed to collect more information and statistics to characterize the spurious pulses. Figure 11 shows a graphic of the some of the data extracted from this test on sc224. It shows the collection of one or more spurious pulses received each spin cycle in advance of the true Sun pulse. In most cases, there were multiple spurious pulses received within a very short amount of time; as many as ten pulses within 8 millisec were observed.

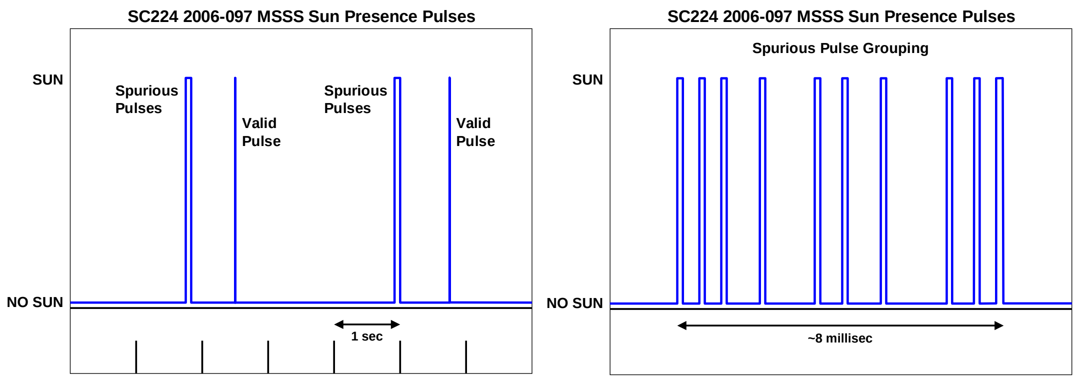

Figure 11: MSSS Sun Presence Pulse Characterization

The only other on-orbit fix applied related to the MSSS anomaly was designed to allow for correct spin rate calculation on the spacecraft. Because the spin rate calculation was based on the Δ times between adjacent pulses, the spurious pulses caused the calculated spin rate to be higher than actual. Given that the Δ times for the true and spurious pulses were approximately 20% and 80% of the true spin period, the calculated spin rates would be higher by a factor of 5 and 1.25, respectively. Existing software limits on the calculated spin rate eliminate the calculation that was five times too high, so the resultant spin rate calculated onboard was 25% too high. Because the onboard spin rate is used in sun acquisition and attitude precession modes to calculate the timing of thruster commands, it was important to have this number be accurate. Five or ten times a day there is a spin cycle with no spurious pulses at all. This fact leads to the method used to calculate a correct spin rate with nothing but simple table changes to the flight software. The three steps needed were:

1. Change the software limits on minimum and maximum spin rate to be ±10% of the expected value,

2. Change the software first-order filter coefficients used to filter the spin rate to effectively disable the filter, and

3. Wait.

By implementing the first two changes, the calculated spin rate "freezes" at the current value, which is 25% high, because the calculated value when there is a spurious pulse is always too high. However, when a spin cycle occurs where there is no spurious pulse, the spin rate calculation gives a correct spin rate within the allowable range, and the spacecraft begins to report and use the correct spin rate. This change was implemented on all three spacecraft, and within a day each spacecraft began reporting the correct spin rate.

Constellation Replanning & Maneuver Performance

Figure 12 shows the nominal constellation planned and timeframe for maneuvers for the three ST5 spacecraft. The plan was for the middle spacecraft in the string-of-pearls constellation to be the reference spacecraft, with planned in-track separation between it and the leading and following spacecraft. After the initial post-deployment separation, the spacecraft would be maneuvered into two science validation constellations for approximately 30 days each.

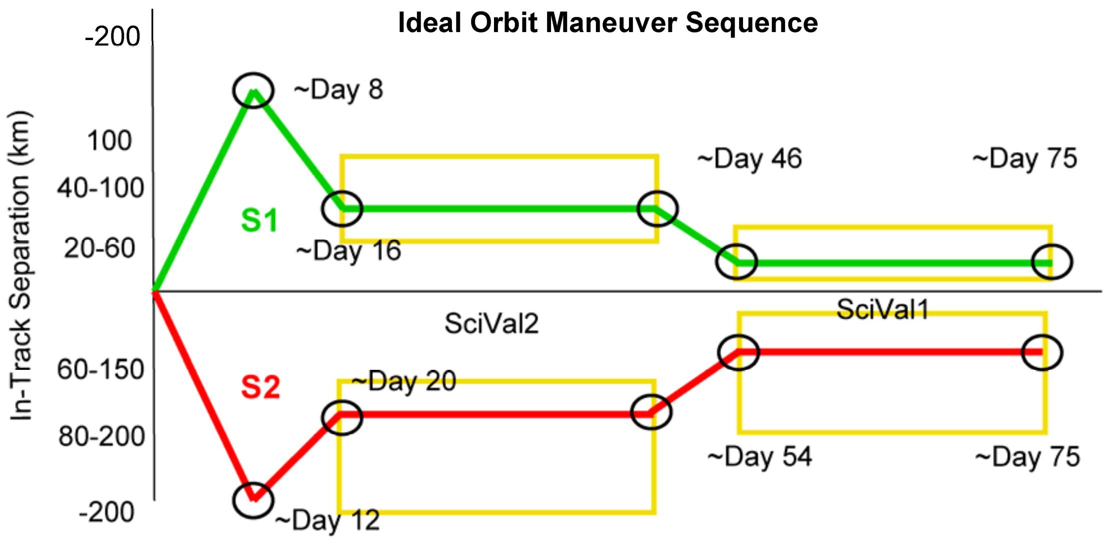

Figure 12: Nominal Constellation Plan

A number of things happened that prevented the original constellation plan from being implemented. As mentioned previously, the rise order of the constellation was different than expected, with sc094 the middle spacecraft instead of sc224. The forward spacecraft, sc155 was separating much faster than expected with respect to sc094 and sc224. To further complicate matters, the Pegasus rocket body ended up within the ST5 constellation, between sc155 and sc094. For the first week of the mission, there were tracking data processing issues that resulted on lost passes and a loss of quality of the orbit solution. These facts and others resulted in a three-week delay in maneuvering sc155 and resulted in a longer time to achieve formation than originally planned. Further, the presence of the Pegasus rocket body within the constellation greatly complicated the planning needed to establish the science constellations. Figure 13 shows the in-track separation derived from the definitive orbit determination of the forward (sc155) and aft (sc224) with respect to sc094. The width of each swath shows the relative separation dynamics of a lead-trail formation in an eccentric orbit. Also noted are all of the attitude precession (ATT) and orbit (ORB) maneuvers actually performed on each spacecraft.

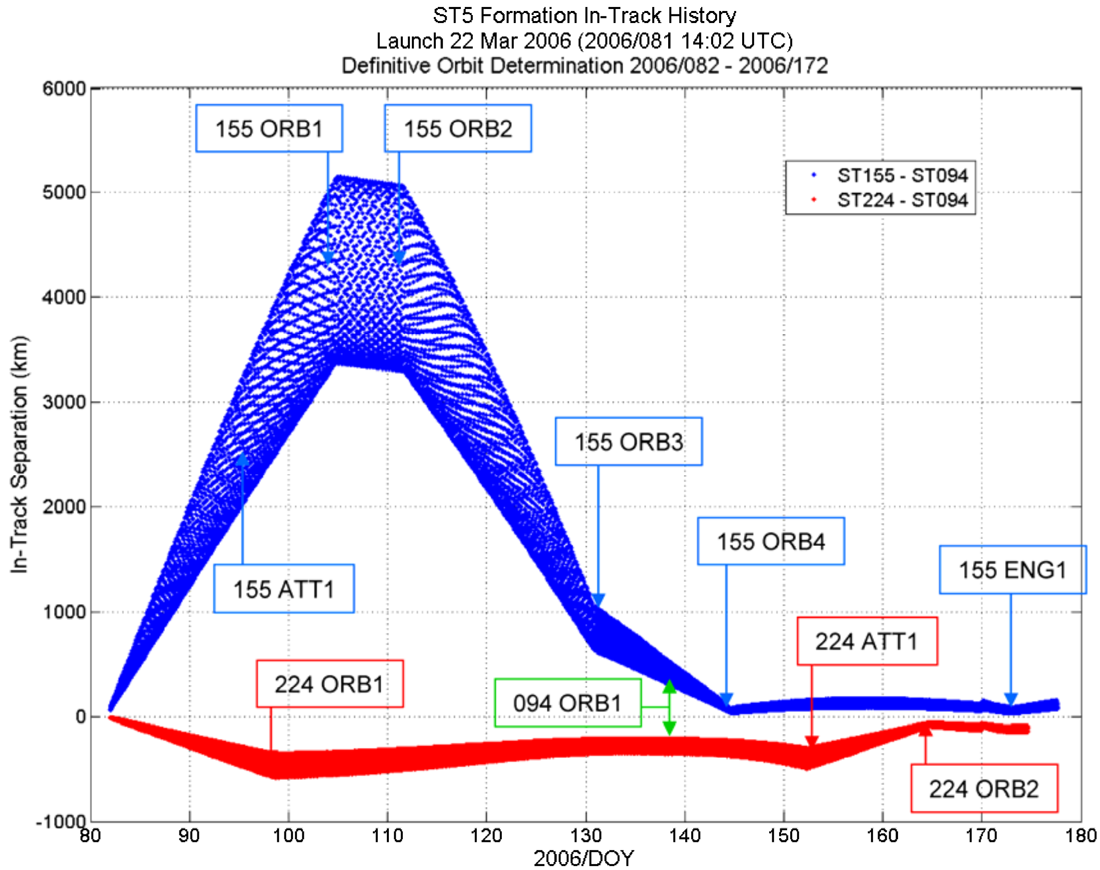

Figure 13: Achieved Constellation History

Spacecraft Spindown

During the first week of operations of the ST5 constellation, the spacecraft flight operations, flight support, and anomaly teams were deeply involved in diagnosing and determining how to work with the spurious pulses being produced by the sun sensor and by operating the three spacecraft. It was during that time, however, that it was first noticed that the spacecraft were all spinning down at a faster rate than expected. Once the sun sensor anomaly investigation and operations worked out, more attention was paid to the spacecraft spin rate decrease and how it would affect future operations.

Once the spin rate decrease was confirmed on all three spacecraft, and shown to be between approximately 0.05 and 0.1 rpm decrease/day (the spin rate over on orbit for sc094 is shown in Figure 14), the team began investigating the possible causes. Because it was observed on all spacecraft, it was unlikely to be the result of a leakage from the cold gas thruster propellant system, and it was confirmed via telemetry that there were no unexpected pressure drops from the propellant tanks. Pre-launch analysis of environmental torques—atmospheric drag, solar pressure, gravity gradient, and magnetic from spacecraft residual dipole—was revisited and it was confirmed that they were too small to produce the observed effect. However, one additional environmental torque was examined to explain the spacecraft spin rate decrease that was not analyzed prior to launch. This additional environment disturbance was torque on the spacecraft caused by the interaction of the Earth's magnetic field with induced eddy currents.

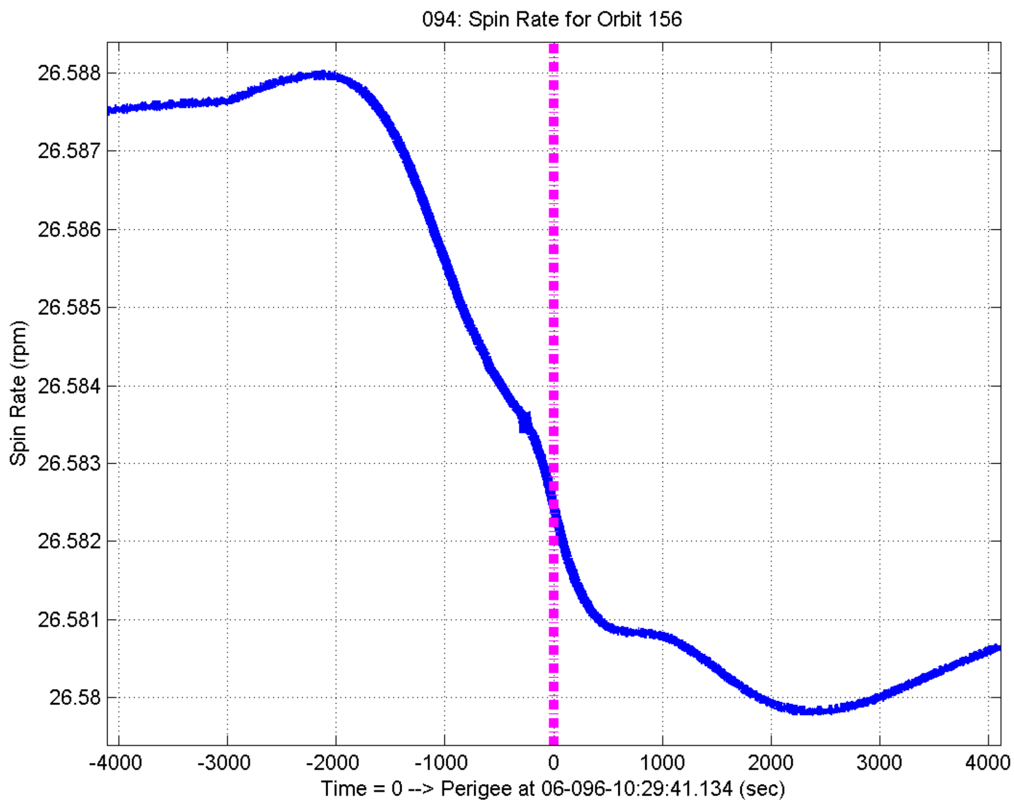

Figure 14: Spacecraft 094 Spin Rate Orbit 156

Dean Tsai of the GN&C flight support team conducted a simulation of the spacecraft over several orbits using the 2005 IGRF-10 magnetic field model. The model included the residual magnetic moment of the ST5 spacecraft, as measured in ground testing, along with an effect due to eddy currents in the spacecraft structure. Figure 15 shows the results of this simulation, with the red dashed line representing the results of the eddy current simulation and the solid blue line showing representative data from sc094 (this plot shows spin rate decrease). This analysis is especially interesting because it provides an explanation for both the general downward trend of the spin rate as well as the periods during the orbit in which the spin rate is increasing: the increase is caused by the residual magnetic dipole while the overall decrease is caused primarily by the induced eddy currents. Guan Le and Jim Slavin of the ST5 Science Team also provided another potential explanation of the observed spacecraft spin down, also caused by interaction of the Earth's magnetic field with the spacecraft. The mechanism, which is similar to eddy currents within the spacecraft structure, is instead carried by leakage current from the spacecraft structure being closed through the surrounding plasma of the Earth's magnetic field. While the project did not have the resources to do enough investigation to identify the exact mechanism for this spin down, the analysis that was performed pretty conclusively showed that it was primarily caused by interaction of the spacecraft with the Earth's magnetic field.

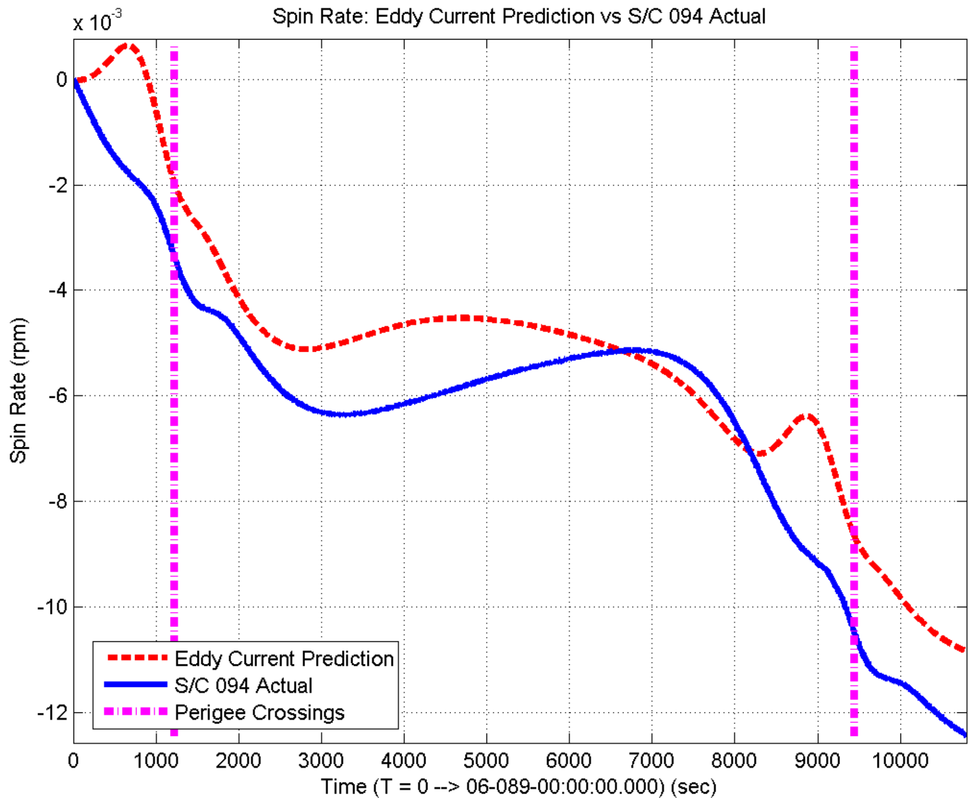

Figure 15: Eddy Current Spindown Prediction vs Spacecraft Data

Because the three ST5 spacecraft each had only one thruster nominally aligned with the spin axis, there was very little that could be done to mitigate the spin rate decrease. Trending analysis showed that the spin rates would not get too low to have a negative effect on spacecraft stability within the planned 90 day mission. During the investigation of the cause of the spacecraft spin down, it was noted that one of the reasons that the eddy current effect was unexpectedly large might be due to the fact that the ST5 spacecraft had a large metal card cage that ended up being perpendicular to the Earth's magnetic field as the spacecraft approached its point of highest latitude and perigee. One possible experiment that could be made to both confirm the influence of the Earth's magnetic field as a cause of the spin down and to mitigate its effect was to reorient the spin axis of one of the spacecraft about the sun line so that when the spacecraft went through perigee the magnetic field lines would not be as perpendicular. This experiment was performed by reorienting sc224 and the fact that the rate of spacecraft spin down decreased provided further confirmation of torque caused by the Earth's magnetic field as the primary contributor to the spacecraft spin down.

Passive Nutation Damper Performance

Figure 16 shows a picture of one of the passive nutation dampers designed and built at Goddard Space Flight Center for use on the ST5 spacecraft, and Figure 17 shows an example of the nutation damper performance, plotting the elevation angle of sc155 after deployment of the magnetic boom. The red dashed line shows the envelope of the nutation damping and can be used to calculate the nutation time constant. This nutation damping information for all spacecraft is depicted graphically in Figure 18. The nutation damper performed as designed.

Figure 16: Nutation Damper

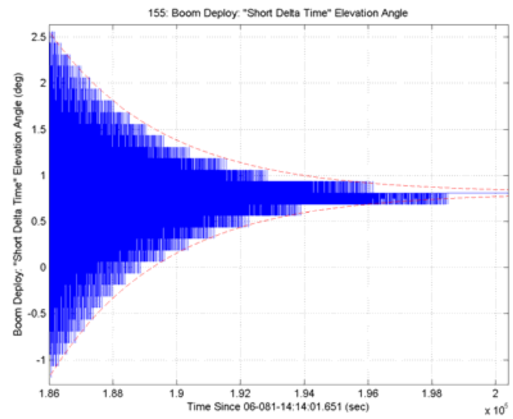

Figure 17: S/C 155 Damper Performance

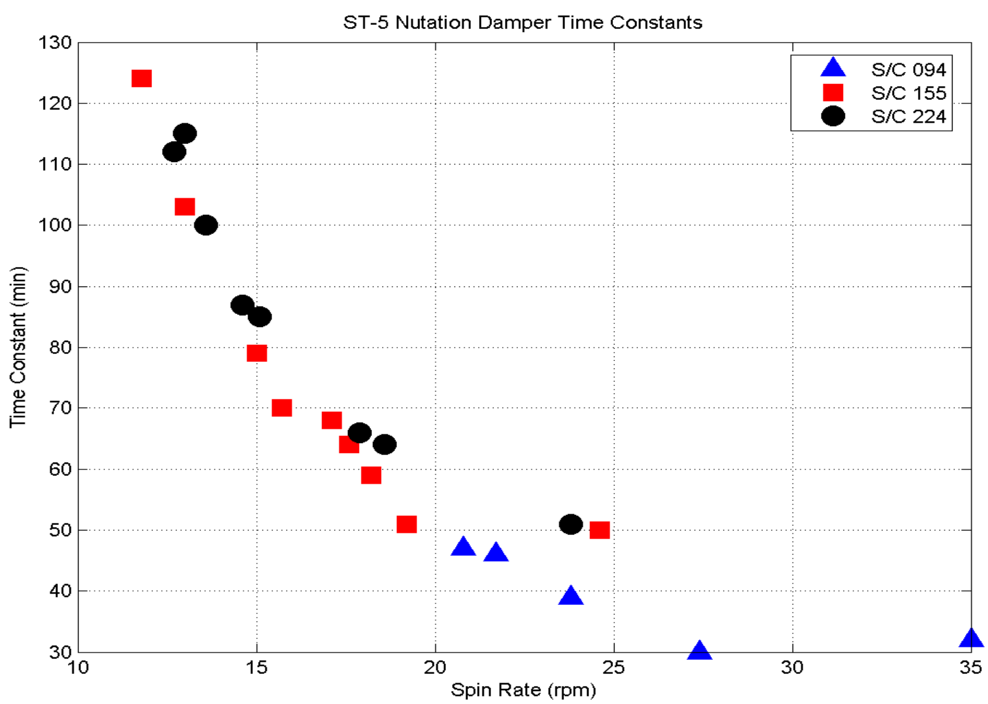

Figure 18: Nutation Damper Performance

Conclusion

On June 1, 2006, the ST5 Project received a Notice of Intent to Terminate Operation of Space Technology 5 Mission letter from the NASA Science Mission Directorate, directing the project to complete end-of-mission activities and cease operations at completion of primary mission no earlier than June 30 and no later than July 7, 2006. The end-of-mission (EOM) activities for ST5 were fairly simple: disable the onboard spacecraft failure detection and correction, empty the propulsion tanks, conduct follow-up passes, and turn off transmitters by not scheduling any further contacts. After conducting these operations, the spacecraft would re-enter the atmosphere well within 25 years and with no debris field, meeting NASA orbital debris requirements. The objectives of the EOM maneuver plan were to fire all of the remaining propellant, configure the spacecraft orbits for eventual disposal (via orbit decay), and minimize recontact probability. Between June 26 and June 29, 2006, a series of 11 EOM thruster firings were successfully conducted on the three ST5 spacecraft and final contact with them was on June 30, 2006.

During a relatively brief 100 day mission and in the face of a number of anomalies, the three ST5 spacecraft were able to successfully satisfy the mission's level one requirements, primarily to design, build, launch and operate three small spacecraft as a constellation in order to achieve accurate, research-quality science measurements. Additionally, ST5 successfully demonstrated a number of new technologies including a miniature communications transponder, variable emittance thermal coatings, a cold-gas micro-thruster, CMOS ultra-low power radiation-tolerant logic, a low voltage power subsystem including LiIon battery, and software tools for autonomous ground operations. The project held the ST5 Technology Symposium to present their results at Goddard Space Flight Center on September 13, 2006.

Project Constellation Support

Introduction

Project Constellation is a NASA program to create a new generation of spacecraft for human spaceflight, consisting primarily of the Ares I and Ares V launch vehicles, the Orion crew capsule, the Earth Departure Stage and the Lunar Surface Access Module. These spacecraft will be capable of performing a variety of missions, from Space Station resupply to lunar landings.

The FDAB's role in Project Constellation is to examine mission design and navigation concepts that support Project Constellation be enabling human spaceflight to the Moon and Mars. The specific efforts are discussed below.

Exploration Communications and Navigation Systems (ECANS)
(POC: Karen Richon, Karen.V.Richon@nasa.gov)

The Project Constellation Program (CxP) levies requirements for communications and navigation/tracking services on NASA Space Communciations and Navigation Program (SCaN). The Exploration Communications and Navigation Systems (ECANS), now known as Space Communication Implementation Project (SCIP), is responsible for making sure the CxP requirements are met using the SCaN resources. In support of CxP and SCIP, FDAB provided lead Navigation Engineers Mike Moreau and Karen Richon, respectively. Mike Moreau held both positions through May 2006, and was joined by Ms. Richon in June when ECANS was more fully defined. Mr. Moreau was also the co-Lead of the CxP Navigation Systems Implementation Group (SIG), which was responsible for defining navigation and tracking requirements and performing analyses to justify and clarify those requirements. As NavSIG Lead, Mr. Moreau interfaced with all Projects within CxP, including the Crew Exploration Vehicle, the Crew Launch Vehicle, the Lunar Surface Access Module, and the various SIGs, including the Communications, Command, Control and Implementation (C3I) SIG, the Flight Performance SIG, and the Ground Operations/Mission Operations (GO/MO) SIGs. Ms. Richon was responsible for working with the Space Network (SN), Ground Network (GN), Launch Head, and other SCaN entities as well as the NavSIG and C3ISIG to help define the requirements and make sure the CxP requirements were understandable and feasible. Support included working with counterparts from many other NASA Centers, ground stations, and JPL.

Lunar Surface Access Module (LSAM)
(POC: Dave Olney, David.J.Olney@nasa.gov)

The FDAB supported a study for a Lunar Surface Access Module (LSAM) in the spring and summer of 2006. This study was part of the definition of Project Constellation elements to include manned lunar exploration. In Phase 1, several NASA centers were asked to create conceptual designs for vehicles to take a crew of four and/or cargo, from the lunar-orbiting Crew Ascent Vehicle (CEV) to the lunar surface. The manned portion of the vehicle, remains up to 30 days on the surface while extravehicular activities are completed, at which time it is launched for rendezvous and docking with the unmanned CEV. The vehicle is then detached and disposed before the CEV returns to earth. Many design concepts were presented. Goddard provided four designs emphasizing that a minimum weight manned ascent vehicle maximizes the cargo weight delivered to the lunar surface. After Phase 1 the potential options were narrowed by the project and for Phase 2, more specific studies from the center teams were requested. Assignments to the GSFC team included a more detailed study of the minimum weight ascent module design. As part of this effort a GN&C baseline was proposed, assuming an operational profile for ascent very similar to Apollo 14–17. Advanced attitude sensors and processors promise substantial weight and power savings compared to Apollo missions.

Lunar Relay – Dave Folta

(POC: Dave Folta, David.C.Folta@nasa.gov)

As part of the Vision for Space Exploration, which sets requirements for Project Constellation with regards to human exploration of the Moon and Mars, FDAB personnel have been supporting various studies including the need for a lunar relay satellite (LRS) to provide both communications and navigation services to users at the Moon. In the near term, plans are being developed to send robotic assets to the lunar South Pole, including sites like Shackleton Crater—a likely location of trapped water ice. As missions are being planned to the lunar South Pole, it is becoming evident that communications with Earth are a potential problem. Investigations into a crater where water ice may be found would likely result in losing direct communications back to an Earth-based control center. Having a relay satellite in orbit about the Moon helps to maintain a link to a lunar surface asset beyond the line-of-sight to the Earth and opens the possibility for real-time, "joystick" operations.

The idea for a lunar relay satellite can be traced as far back as the Apollo program when a relay was proposed to be placed at the Earth-Moon L2 (EML2) libration point on the far side of the Moon. An EML2 orbiter would be ideal for providing communications services for critical operations on the far side of the moon (e.g. orbit insertion). There exist several drawbacks to using an EML2 orbit for a relay satellite, including poor visibility of the poles and the range between the relay satellite and the surface user – in excess of 40,000 km. This extended range would place undue burden on the user in the form of power and antenna size in order to close a communications link. For these reasons, a different orbit is being investigated that can reduce the range to the user as well as increase the availability of service.

The current baseline for a LRS is to use an inclined, elliptical, frozen orbit (Figure 19). Discovered independently by engineers at GSFC and JPL, lunar frozen orbits were found to exist in spite of the Moon's non-homogeneous gravity field. The frozen orbit selected for the lunar relay is a 12-hour orbit with an eccentricity of 0.6. These characteristics yield a 718 km by 8090 km orbit. The selection of an inclination of 57.7° and an argument of periapsis of 90° effectively "freezes" the orbit. This means that there are minimal changes in key orbit parameters (semi-major axis, inclination, and argument of periapsis) due to orbital perturbations. In fact, simulations have shown that this is a very stable orbit, requiring no stationkeeping maneuvers for upwards of 100 years.

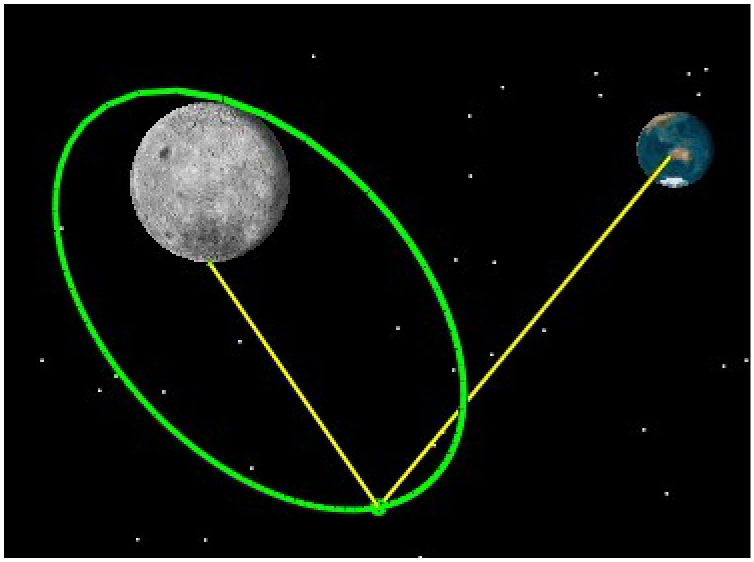

Figure 19: Lunar Relay Satellite Access to South Polar User

Analysis of this orbit has shown coverage of a lunar South Pole asset of up to 63%. Further studies show that a constellation of two satellites in this frozen orbit phased 180° apart from each other could provide 100% coverage of the South Pole. Combining this constellation with a potential Earth-based ground network of 3 strategically spaced antennas (e.g. the DSN or some other combination) allows for continuous communications with the lunar South Pole.

Currently, the LRS team is studying the feasibility of implementing this concept on a small satellite to support near-term robotic landers. Flight dynamics personnel are supporting the development of a concept of operations for the relay system. This includes analysis of a candidate spacecraft that could be flown on a small launch vehicle such as the proposed Minotaur-V. Trade studies currently in work involve the communications payload, navigation hardware and services, propulsion system (electric vs. chemical), antenna and solar array placement, and ground system.

Mars Atmosphere and Volume Evolution (MAVEN)
(POC: Dave Folta, David.C.Folta@nasa.gov)

Support of the Mars Atmosphere and Volume Evolution (MAVEN) Mars Scout proposal consisted of providing validation and verification of contractor analysis and consultation in the IMDC and proposal generation phase. The FDAB provided mission design analysis for launch windows, transfer trajectories, arrival conditions, aerobraking, and orbit selection, variation, and maintenance. Presentations were made to several groups during this process. Figure 20 and Figure 21 show a sample transfer case and a mission orbit option, respectively. A traditional transfer using a minimum energy launch profile was used. As mentioned previously, variations in the orbit about Mars due to planetary and third-body perturbations were investigated. Using the Mars GRAM atmospheric model, aerobraking trades were performed for various ballistic properties and initial apoapsis conditions that result in achieving the mission orbit in the allotted timeframe. Transfer geometry analysis, including communication coverage analysis, distances to the Earth, Mars, and the Sun, along with transfer ΔV/fuel budget for insertion into orbit was performed. Launch, cruise, and insertion navigation requirements analysis were provided as an overview based on current operational methods using S-band tracking and differenced Doppler.

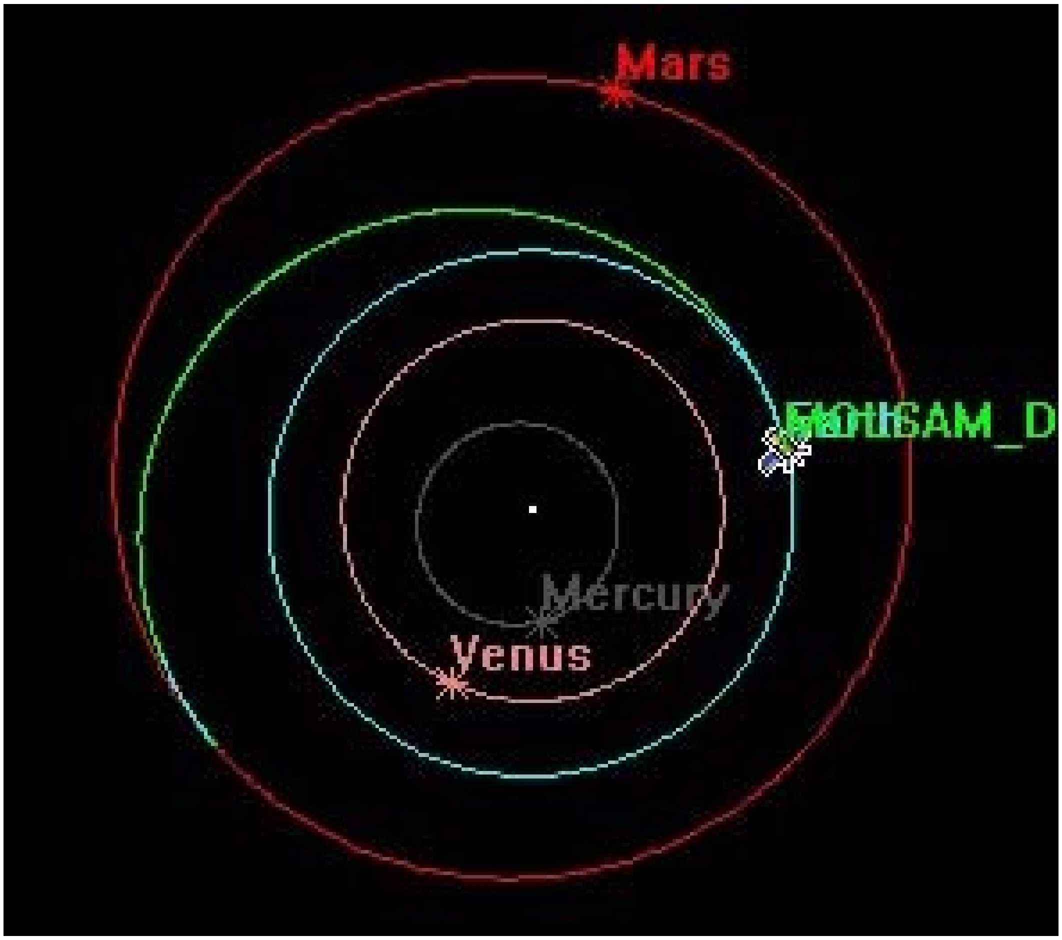

Figure 20: MAVEN Transfer Trajectory

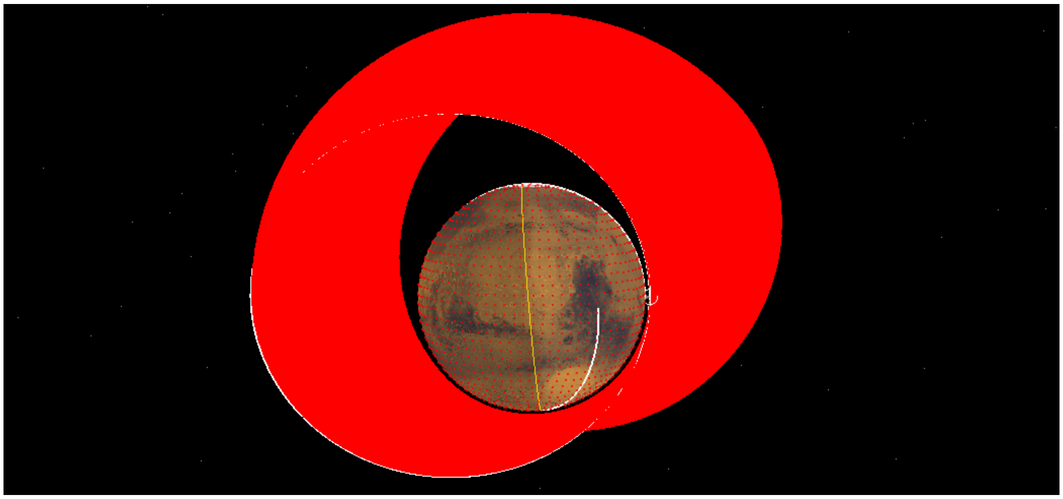

Figure 21: MAVEN Orbit

Innovations and New Capabilities

Introduction

As a world leader in flight dynamics technology, the Flight Dynamics Analysis Branch (FDAB) has continued to pursue new techniques and capabilities to facilitate our work. Several of these new capabilities include extensive visual elements and hardware in the loop simulations that significantly improve the analyst's understanding of the increasingly complex integrated dynamics of the orbit, attitude, and control environment. In order to reduce response time to mission analysis requests from established or future missions, new tools are being developed to allow analysts innovative means to perform studies that offer flexibility to include mission-unique features. The new tools are meant to be platform independent and to rely on programming languages that are most effective in implementing the algorithms needed by the analyst. Tools that are geared for an operational environment also incorporate a GMSEC-compliant architecture.

Freespace
(POC: Steven Queen, Steven.Z.Queen@nasa.gov)

Freespace is a spacecraft simulation environment developed over the past few years at GSFC by the FDAB. It originated with the Hubble Robotic Servicing and Deorbit Mission (HRSDM) in order to address the need for a mission simulator and analysis tool that encompassed multiple spacecraft for rendezvous and capture, as well as multi-body (robotic) and vision system elements. Freespace runs on a number of Unix-based operating systems (Linux, IRIX, OS X), and is inherently multi-process/multi-threaded, targeting the highest-performing computing hardware. Elements of the system include a MATLAB compatible pre- and post-processing scripting parser, an optimized run-time engine employing advanced numerical integrators that operates on reconfigurable functional modules (coded in C), an integrated control mode management system, and a powerful visualization back-end built with a custom scene graph (C/OpenGL 2.1) and multiple GPU shaders. It has been used successfully on a number of in-house missions including HRSDM, GPM, Lunar Reconaissance Orbiter, SM4/RNS and Magnetospheric Multi-Scale. Its development goal is to streamline the typical GN&C analysis work-flow, deliver cutting-edge computing capabilities (e.g. hardware accelerated dynamics and real-time photo realistic visualization), and serve as a real-time (hardware-in-the-loop) node in the spacecraft integration and testing processes. Figure 22, shows Freespace visualizations of the Hubble Servicing Mission 4.

Flight Dynamics CAVE
(POC: Dave Folta, David.C.Folta@nasa.gov, and Steven Queen, Steven.Z.Queen@nasa.gov)

Flight dynamics analysis requires the use of innovative methods to address the increasingly complex nature of designing exploration and science missions. These complexities derive from the need to visualize mission requirements and operations and from using advanced methods such as dynamical systems to design missions. The Vision for Space Exploration requires innovation to fully understand and apply advanced technologies and astrodynamics to optimal designs, lunar rendezvous and docking, collision avoidance, and libration orbit formation flying, all which must be viewed in a three-dimensional environment to be fully understood.

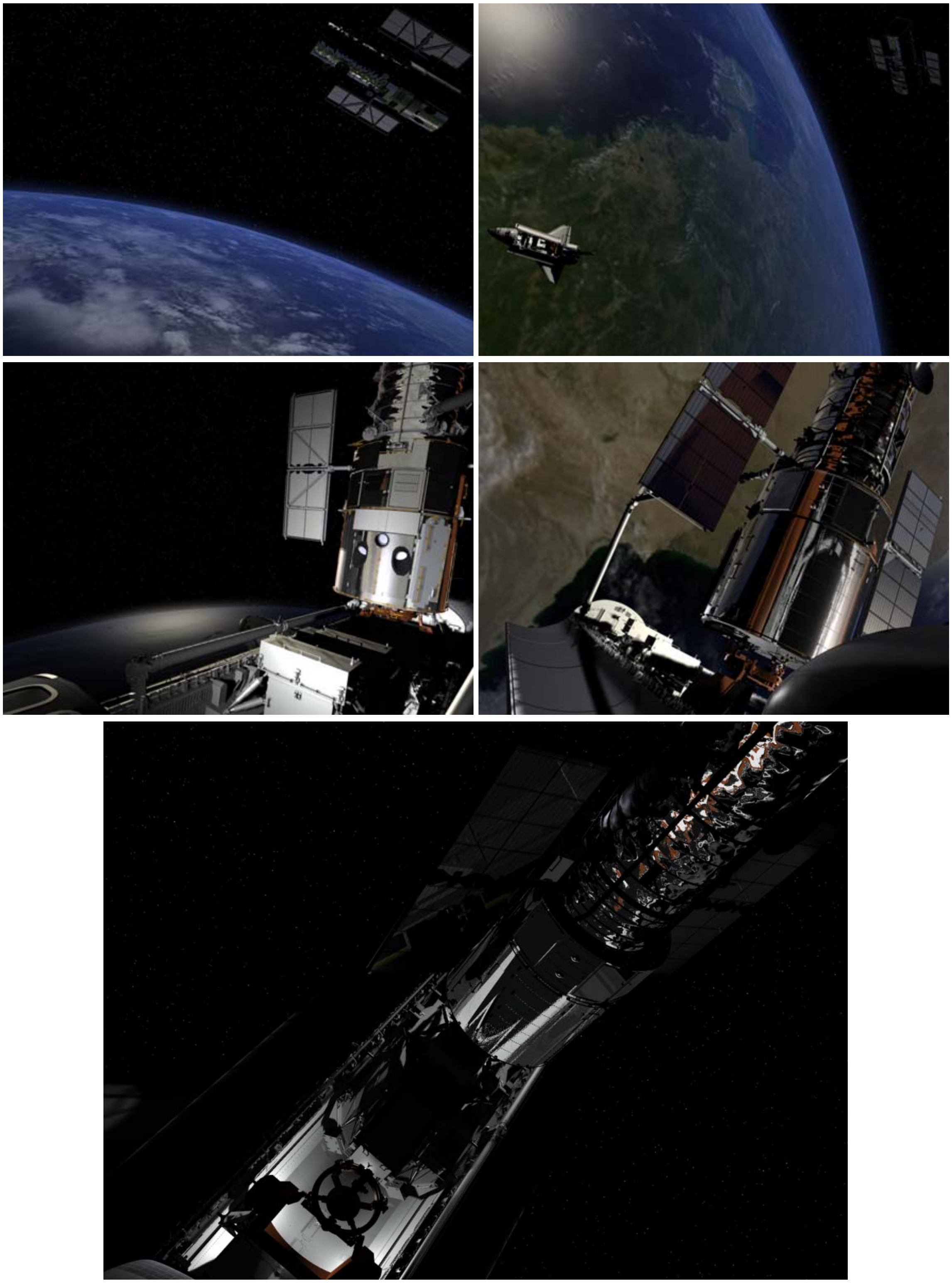

Figure 22: Freespace Visualization of Space Shuttle Rendezvous with the Hubble Space Telescope During Servicing Mission 4

To meet these needs, we are developing and installing a 3-Dimensional mission design visualization capability, commonly called a CAVE (see Figures 23 and 24), by integrating commercial components with the Flight Dynamics Facility (FDF) capabilities to enable GSFC to support upcoming exploration and science missions using advanced technologies. We then will be able to integrate our high-fidelity analysis tools directly into this system, thus allowing us to provide support for the design, operations, and investigation of any mission by directly manipulating 3-dimensional objects. The Cave will allow GSFC to advance the state of the art mission design tools.

Figure 23: Trajectory Design Analysis in the Cave

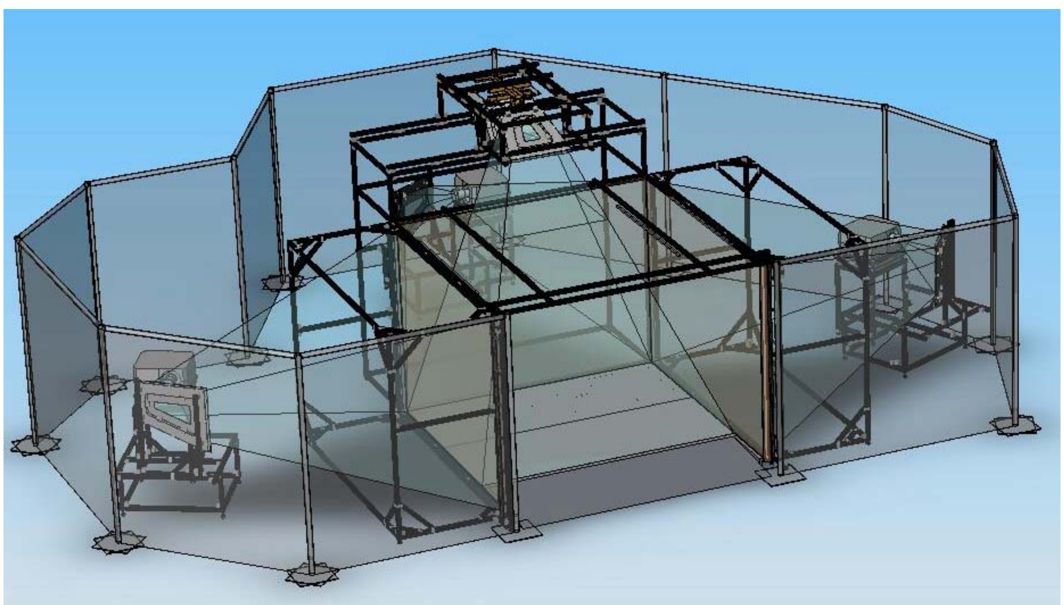

Figure 24: Skeleton Drawing of the CAVE Components

We are leveraging the Freespace simulator, originally developed for the Hubble Robotic Servicing Mission that is an integrated spacecraft mission design and testing environment. Its high performance engine utilizes multi/parallel processing, multi-graphics pipes and extended (128-bit) numerical precision to enable very high fidelity end-to-end testing of Guidance, Navigation, and Control (GN&C) systems. It targets challenging multi-spacecraft and/or multi-body dynamics applications with the need for man/hardware-in-the-loop hard (>1 KHz) real-time capabilities or advanced video image generation. A development effort submitted under a related IR&D proposal ("High Performance Simulation Design & Testing Environment Development") will procure the necessary computing equipment to control this immersive CAVE environment. Rendering of engineering displays or virtual remote sensing data are endemic to the Freespace design and will only require a small level of effort to bring it to fruition. The details are: a 4-sided CAVE (3 walls and a floor) using DLP projectors and mirrors at 1440x1024 resolution. The approximate system footprint will be around 30 x 25 x 15 feet and will give an 11 x 11 x 11 immersive environment. We will use 8 graphics pipes (2 per wall) in a Linux based visualization system from SGI and Christie Digital Systems, multiplexed for active stereo using hardware compositors to combine the pipes. A tracking headset, command wand and wireless eyewear will also be needed as will the CAVElib software.

The use of three-dimensional visualization will permit a level of advanced flight dynamics analysis (orbit, attitude, formations, etc.) that has not yet been achieved at GSFC. This effort will permit us to both view analysis and make operational decisions regarding missions that are too complex to envision with 2-D output. Equivalent to going from a mainframe with paper output to high-end PC gaming, the end result of this IRAD will allow GSFC and NASA to take the next step in GN&C research and trajectory design. We will integrate our high fidelity trajectory design software to enable a mission designer new capability by allowing manipulation of orbits and attitude dynamics as input to analysis. The Cave environment will not just be a static tool for showing results, but a process to allow the analyst to design in true 3-dimensions. We will be able to share the research in real-time by observing and analyzing the results generated in near-real time using spacecraft telemetry.

It is anticipated at this writing that the CAVE will be online at the beginning of June 2007.

Java Tool Development
(POC: John Downing, mailto:John.P.Downing@nasa.gov)

Pyxis is a prototype graphical mission design tool for first guess analysis of multiple planetary flybys. While it has proved useful in designing missions such as Solar Sentinels and Icy Moon/Enceladus, it has stability problems related to the Borland compiler used. Since the Borland GUI (Graphical User Interface) library used for tool development is over ten years old and is no longer supported, it was decided to begin porting the code to Java, a more modern language with built-in platform independent GUI libraries. The basic libraries are shared with Solar Pressure & Aerodynamic Drag (SPAD) and INteractive Controls Analysis (INCA). These have been ported, as well as the code for ephemeris, magnetic field, solar flux and gravity model calculations. Time scale and Atmospheric model is partially ported. More complex atmospheric models would benefit from a Fortran to Java converter, not currently available. Work on converting Pyxis tool has begun, but there is considerable work to do before it is useful. Surprisingly, the Java code runs nearly as fast as C++, and much faster than Matlab code.

Actuator Sizing Tool

(POC: Kristin Bourkland, Kristin.L.Bourkland@nasa.gov)

An Actuator Sizing Tool was developed in previous years and was updated to Version 2.0 during FY2006. The tool, which was created in Matlab and Simulink, uses a GUI (Graphical User Interface) to input spacecraft parameters, and then outputs the required sizing for reaction wheels and/or magnetic torquer bars due to environmental torques. The GUI interface is shown below in Figure 25.

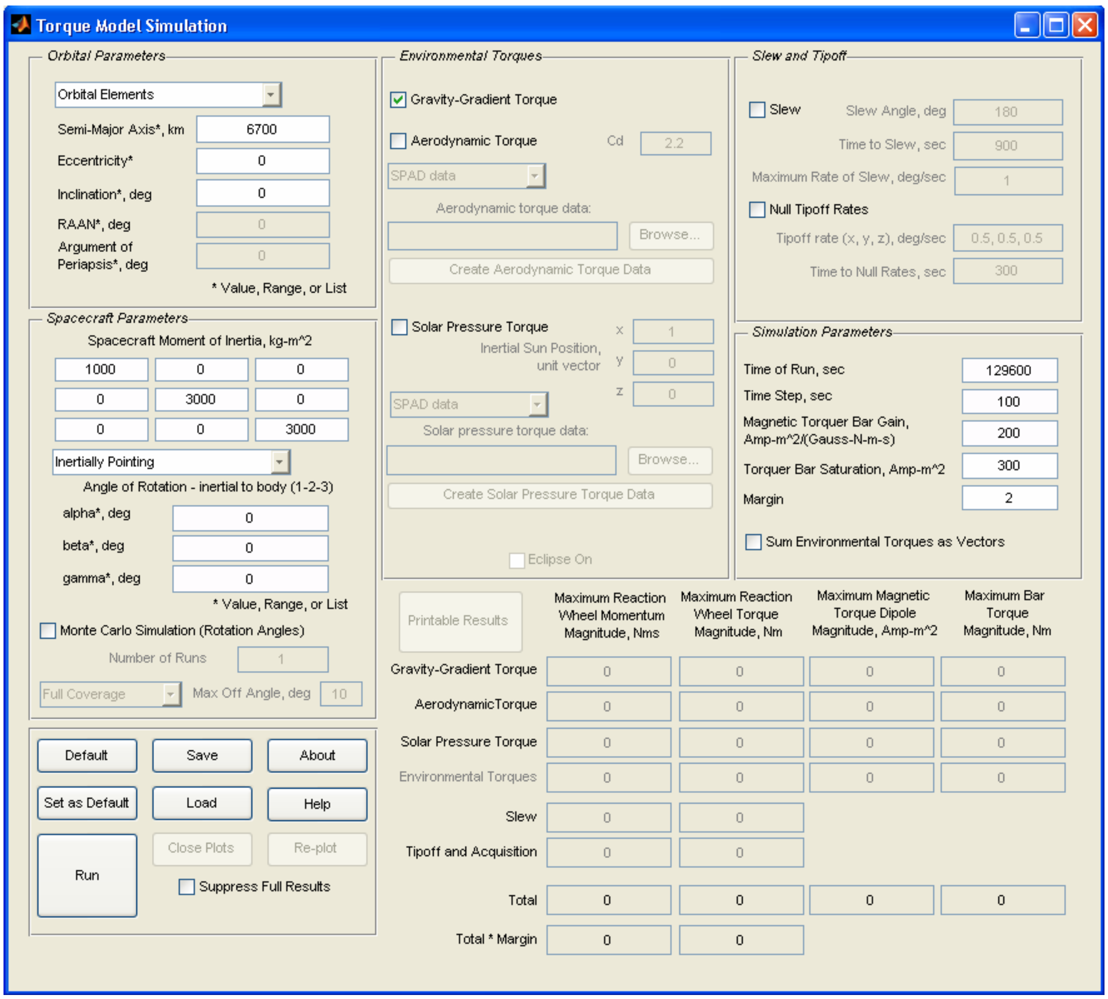

Figure 25: Actuator Sizing Tools Graphical User Interface

Updates were made this year to fix errors that were apparent in the previous version, as well as to make the tool more universally useful. Additionally, the documentation was expanded to include a description of all available features. The most complex change involved including additional options for defining the orbit and attitude. Version 2.0 allows the user to define the orbit in terms of position and velocity, as well as in the form of orbital elements. Also, the attitude can be defined as nadir pointing or inertially pointing. Another update involved the way that torques, which are due to environmental effects, are handled. The default tool settings consider each environmental torque separately, and then sum the sizing results due to each torque. An option was added to sum the environmental torques as they occur, so that there may be constructive interference in the sizing.

An additional effort was made to make the sizing tool as user-friendly as possible. Previously, results were only available for viewing on the screen after a simulation run was made. Version 2.0 allows the user to save the data to a file in various forms for future viewing. Also, other ways to input data were included in the tool. The updated version allows the user to specify parameters defining aerodynamic and solar pressure torque inputs instead of requiring a file to be input.

General Mission Analysis Tool (GMAT)

(POC: Steven Hughes, Steven.P.Hughes@nasa.gov)

The General Mission Analysis Tool (GMAT) is a collaborative development project being developed at Goddard Space Flight Center with partners in private industry. The system is designed to support complex missions in flight regimes ranging from low Earth orbit to lunar applications, interplanetary trajectories, and other deep space missions. The project was submitted for open source release under the NASA Open Source Agreement in November 2005. We will complete the transition to a public, open source release by Fall of 2007.

GMAT supports numerous capabilities that are listed in Requirements and Mathematical Specifications documents. Among the most important capabilites supported by GMAT are: orbit propagation, maneuver modelling using finite and impulsive models, differential correction, optimization through the use of Non Linear Programming, time-synchronized propagation of distributed spacecraft, in line mathematics in the mission sequence using the same syntax as the MathWorks' MATLAB® system, plots and reports, and control flow.

A user can interact with GMAT using either a graphical user interface (GUI) or through a custom scripting language, designed to make GMAT scripting very easy for users familiar with scripting with the MathWorks' MATLAB® system. All of the system elements can be expressed through either interface: users can configure elements in the GUI and then view the corresponding script, or write script and load it into GMAT. The system contains components that display trajectories in space, plot parameters against one another, and save parameters to files for later processing. The trajectory and plot capabilities are fully interactive, plotting data as a mission is run and allowing users to zoom into regions of interest and view data in any coordinate system. Figure 26 depicts a GMAT screen showing the visual tools and the script.

This year we've made numerous enhancements to GMAT by adding new capabilities, strengthening the system's documenation, and performing rigorous testing and validation. Perhaps the most significant new addition is a Non-Linear Progarmming (NLP) component. The NLP component allows the user to perform constrained Non-Linear optimization by varying any set of parameters in GMAT, to optimize a general set of cost and constraint functions defined using either internal parameters or in-line math statements. To demonstrate the generality of the optimizaton component, test problems were solved that are purely mathematical in nature, and not related to mission analysis or orbit design. The inline math component, enabling the general optimization capability was also implemented this year.

Documentation enhancements in 2006 focused on the GMAT Architectural Specification, the GMAT System Test Plan and the GMAT Validation Test Plan. Architectural specifications for the Script Interpreter, inline math, and optimization components were completed. Also, design enhancements were documented that allows GMAT to handle any type of GMAT parameter (variables, arrays, array elements, spacecraft properties) in all commands. The System Tests Plan and Validation Test Plan were both writtin this year. System and Validation testing was performed according to the test plans and was completed in Dec. 06.

GMAT is currently being prepared for Beta release in May of 07.

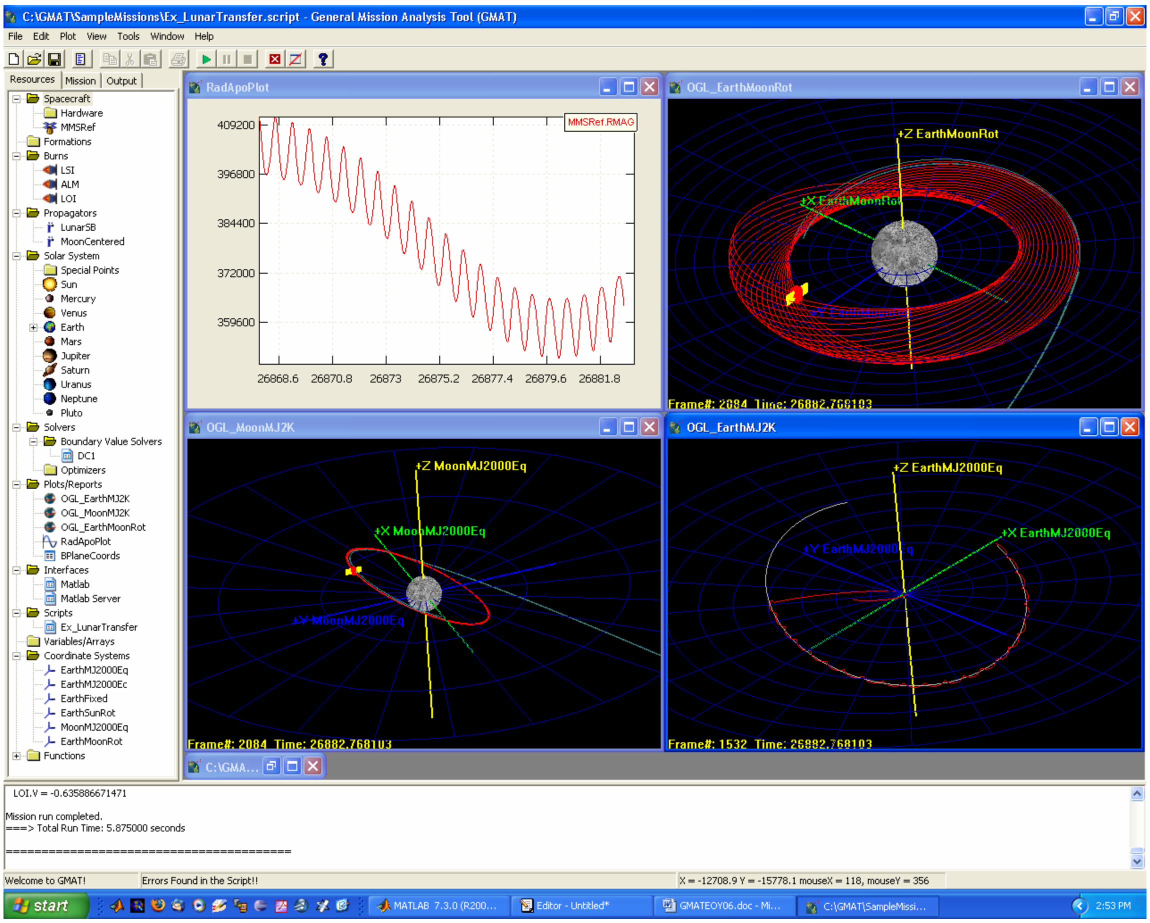

Figure 26: Screen Snap Showing GMAT Visual and Scripting Interfaces

<u>Orbit Determination Toolbox (OD Toolbox)</u>
(POC: Kevin Berry, Kevin.Berry@nasa.gov)

The OD Toolbox is an orbit determination (OD) analysis tool set based on Matlab and Java, which provides a much more flexible way to perform early mission analysis than is possible with legacy tools. Matlab is the primary user interface, and is used for implementing new measurement and dynamics models from a library of base classes, rather than making a major software change every time a new mission proposal come up, particularly one that implements new flight dynamics technologies. The OD Toolbox uses extensions of the Java Astrodynamics Toolbox (JAT) as an engine for routines that might be slow or inefficient in Matlab, like high fidelity trajectory propagation, lunar and planetary ephemeris lookups, precession, nutation, and polar motion calculations, ephemeris file parsing, etc. The tool set primarily serves the needs of conceptual mission studies, which are frequently performed for proposals, the IMDC, and during

Phase A of approved missions. We expect that as it matures, it will also be of particular utility to formation flying and exploration missions, which make extensive use of novel combinations of onboard sensors. A key element of the effort is the extension of the GMSEC middleware-based architecture to domains outside of mission operations and ground systems development and integration. The OD Toolbox is designed to "publish and subscribe" to a GMSEC-compliant "software bus," to enable the exchange of data with our flight dynamics tools, such as the General Mission Analysis Tool (GMAT).

The objectives for development spirals two and three were completed. Highlights include completion of the GMSEC file transfer code for Windows and Linux, incorporation of an OD Toolbox installer, and further additions to JAT's functionality. Parsers were added to JAT to read Global Positioning System (GPS) data in RINEX and SP3 file formats, linear and Lagrangian interpolators were added to JAT's integrator, and adaptors were created to allow Matlab to send commands into JAT.

GPS Enhanced Onboard Navigation System (GEONS) Ground Support System (GGSS)
(POC: Bo Naasz, Bo.Naasz@nasa.gov)

In 2006 the FDAB continued its onboard navigation tool development with several software releases of the GPS Enhanced Onboard Navigation System (GEONS), and a new user interface and flight support tool called the GEONS Ground Support System (GGSS).

Improvements to GEONS included three new releases in 2006. Release 2.5 contains improvements to meet GPS modernization requirements for dual frequencies/bands (L1, L2, L5I5, L5Q5). It also includes Low Thrust Navigation acceleration bias estimation capability, and the capability to estimate time bias and drift using a first-order Gauss Markov process model. Release 2.6 features include enhanced output options, improved lunar gravity model integration, verified by benchmark from GTDS (Goddard Trajectory Determination System), capability to estimate a lander 2-D position on the Moon, and improved antenna models. Release 2.7 includes additional antenna model enhancements in the Data Simulation Program, additional Low Thrust Navigation capabilities, Gauss-Markov process models for bias, drag, and Solar Radiation Pressure states, and several other minor enhancements.

The new GGSS tool is a user interface to GEONS that provides increased usability of GEONS for pre-mission analysis. Future builds will provide the additional components required in a Flight Dynamics Ground Support System of a mission using GEONS, providing an automated system on the ground to support onboard navigation. The GGSS will provide a means for calibrating the onboard navigation system, assessing the quality of the onboard navigation solutions, monitoring the performance of the system over time, and distributing the associated flight dynamics products. The GGSS will also incorporate the GEONS software for ground processing.

Together, GEONS and GGSS provide a critical GSFC navigation tool. Development of user interfaces to GEONS and its associated utilities, and implementation in the next fiscal year of a Monte-Carlo capability in the GGSS will vastly improve the capabilities at GSFC to perform navigation analysis for a broad spectrum of missions.

Conjunction Assessment for the Earth Science Constellation (ESC)
(POC: Lauri Newman, Lauri.K.Newman@nasa.gov)

Since November 2004, the FDAB has been performing Conjunction Assessment analysis for the Earth Science Constellation (ESC) fleet of ten spacecraft. Cheyenne Mountain screens ephemeris data provided by each mission owner against the space object catalog, and provides the resulting state and covariance data to FDAB. Task personnel evaluate the threat of collision between identified objects and the ESC assets using an in-house developed automated tool suite that can determine the closeness probability between an asset and an object, detect the sensitivity of the conjunction to the asset's orbit determination characteristics, and analyze the effect of various potential avoidance maneuvers on the asset's orbit and science requirements. Screening data is stored in a database and trended to obtain statistics on the debris environment. For instance, Figure 27 shows that, on average, two objects come within 1 km of each spacecraft each month.

To date, the Terra spacecraft has had to perform one debris avoidance maneuver to mitigate a $1x10^{-2}$ chance of collision with a well-tracked object. Experience with this event, as well as documentation of the FDAB Conjunction Assessment (CA) process and a description of the tools is available in five papers that were presented at the AIAA Astrodynamics Specialist Conference in Keystone, CO in August 2006. The FDAB system can be used for any orbit regime, and FDAB has performed analysis for the other missions, including ST-9, NPOESS, and NPP as they prepare for facing the debris environment after launch. FDAB is currently working with the Office of Safety and Mission Assurance at NASA Headquarters to consolidate and strengthen Goddard's Conjunction Assessment capabilities.

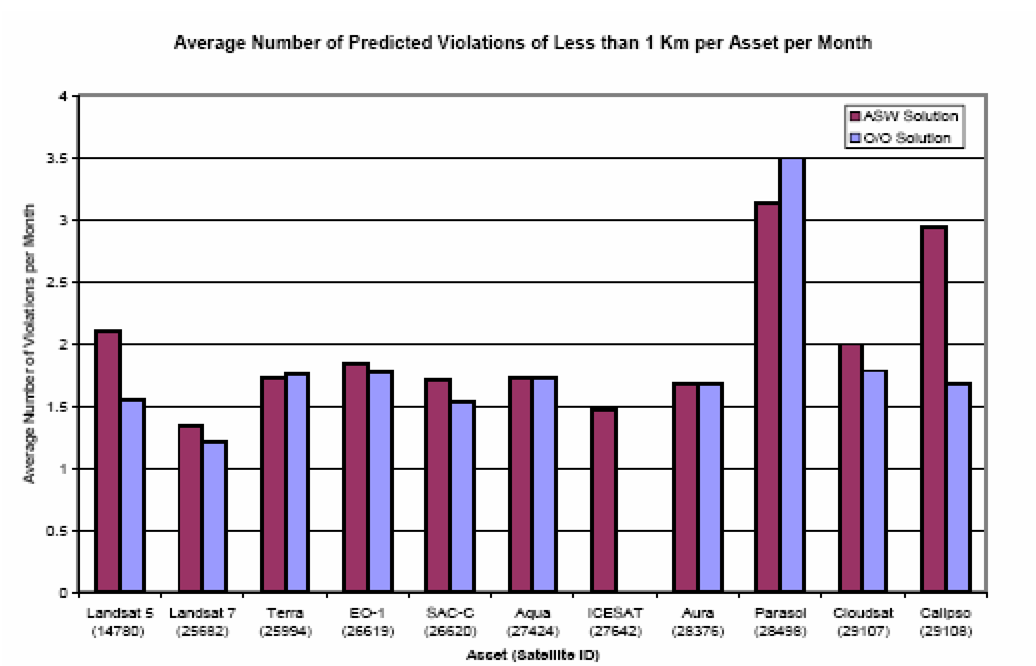

Figure 27: Average Number of Violations < 1 km per Spacecraft per Month

In-House Mission Support

Introduction

The Flight Dynamics Analysis Branch (FDAB) has supported the following in-house missions during the 2006 fiscal year: Solar Dynamics Observatory (SDO), Lunar Reconnaissance Orbiter (LRO), Magnetospheric Multi-Scale Mission (MMS), and Global Precipitation Measurement (GPM). Each mission poses various challenges, from taking measurements of the Earth's atmosphere to flying spacecraft in formation and journeying to the moon. Below is a detailed description of each mission including technical contacts.

Solar Dynamics Observatory (SDO)

(POC: Scott Starin, Scott.Starin@nasa.gov, and Robert Defazio, Robert.L.Defazio@nasa.gov)

Introduction

The Solar Dynamics Observatory (SDO) is a cornerstone mission within the Living With a Star (LWS) program, a program dedicated to the study of the Sun-Earth connection. SDO will observe the Sun's dynamics to increase understanding of the nature and sources of solar variability. The spacecraft will host a complement of three solar science instruments. The Helioseismic and Magnetic Imager (HMI) will study solar variability and characterize the Sun's interior and the various components of magnetic activity. The Atmospheric Imaging Assembly (AIA) will provide full-disk imaging of the Sun in several ultraviolet and Extreme-Ultraviolet (EUV) band passes at high spatial and temporal resolution. The Extreme-Ultraviolet Variability Experiment (EVE) will measure the solar EUV irradiance with unprecedented spectral resolution, temporal cadence, accuracy, and precision (see Figure 28).

SDO will be placed in an inclined geosynchronous orbit where it can maintain constant uninterrupted contact with the ground. SDO will produce an average science data rate of 130 Mbps that will be continuously down linked to the ground and relayed in near real-time directly to the principal investigator teams at their respective Science Operations Centers (SOCs). The SDO ground system will include a dedicated antenna system and a Data Distribution System (DDS), both located at White Sands, NM. The Mission Operations Center (MOC), located at GSFC, will be the focal point for the monitoring and control of the observatory and ground system operations. Within the SDO MOC the Flight Dynamics System will perform a variety of services and product computations to support the health and safety of SDO as well as maintaining the mission orbit and providing product for science planning.

Launch and Early Orbit

SDO will be launched aboard an Atlas-5, 401 launch vehicle from the Eastern Test Range during the third quarter of 2008. The SDO transfer orbit design will meet the Project constraints for power, thermal and communication during Launch and Early Orbit (L&EO). Following separation the ACS Team will handle non-nominal tip-off rates and point the principal spacecraft axis at the sun. During L&EO momentum build-up will also be controlled. Orbit determination during this period will be performed by the Flight Dynamics Facility at GSFC with orbit solutions delivered to the MOC/FDS. Current planning consists of seven orbit raising maneuvers to place SDO in its mission orbit which is an inclined, geosynchronous orbit with the spacecraft contained in a +/- 0.5 degree longitude box. The longitude is maintained by approximately two East-West station keeping maneuvers per year. Additionally, a momentum management maneuver is planned every 4-5 weeks.

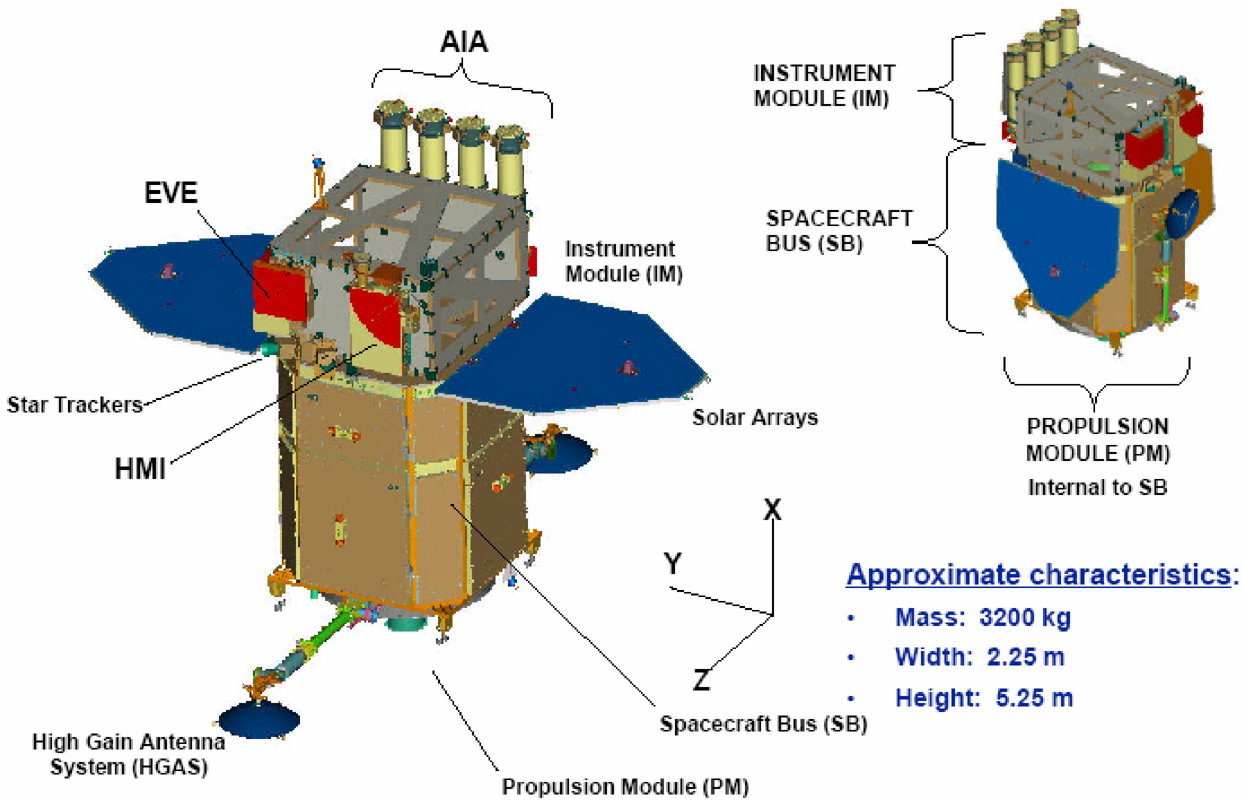

Figure 28: SDO Spacecraft Schematic

Mission Operations Center / Flight Dynamics System

Within the SDO MOC the Flight Dynamics System (FDS) is hosted on a series of four high-end personal computers. During both L&EO and Mission Orbit spacecraft operations, the FDS performs the following major functions: Orbit Maneuver Control, Attitude Determination (batch and real time), Attitude Control and Orbit and Attitude Product Generation. Included in these functional areas are attitude sensor calibration, High Gain Antenna (HGA) calibration, momentum management support, SDO instrument calibration planning and orbit circularization and station keeping maneuvers. One major Flight Dynamics function, orbit determination, is performed for all mission phases in the GSFC Flight Dynamics Facility.

Flight Dynamics Accomplishments in 2006

In 2006, the Flight Dynamics Team concentrated on building and testing the MOC/FDS software. Releases 1 and 2 were delivered in 2006 and all testing was completed except for a few items that were part of Release 2. The next major contribution by Flight Dynamics in 2006 was the work performed on analyzing, planning and implementing procedures for High Gain Antenna (HGA) operations, including handover procedures. During two separate 70+ day periods of each operational year, the daily operations require that the handover of operations from one HGA to the other occur due to spacecraft blockage of the first antenna. Another major task of the Flight Dynamics Team was working with the launch vehicle trajectory design team to design the launch portion of the mission to meet all Project constraints.

Attitude Control Accomplishments in 2006

The past year saw the completion of the flight software (FSW) that will execute the various SDO attitude control modes. The Attitude Control Electronics box will house the microprocessor responsible for executing Safehold mode; build 2.1 of that software was built and was being tested as we began 2007. The command and data handling main processor also runs the Attitude Control (AC) and Ephemeris (EP) tasks.

The AC task provides control torques to reaction wheels and thrusters, depending on the active control mode. The EP task provides the SDO system with information on the positions and velocities of the Sun, Earth, Moon, and Observatory with respect to each other, for purposes of field-of-view obscuration prediction and velocity aberration correction for the automated star trackers and the digital Sun sensor. The ACS team has also provided assistance to the independent flight software testing team by helping to identify simulation scenarios appropriate to the ACS and FSW requirements being tested.

Observatory Jitter Analysis

During 2006, significant amount of effort was dedicated to testing SDO jitter from critical components and assemblies. The SDO jitter team measured 3-axis force and torque disturbances generated by the high gain antenna (HGA) gimbals and the EVE filter wheel mechanism. The resulting hardware test data were used for updating the disturbance input models which drive the observatory structural and optical models for predicting the jitter performance. In addition to the standard modal survey test, structure component tests were performed at GSFC where stingers were mounted at various locations to excite the bare bus structure and the HGA boom. The accelerations induced by stinger excitations were measured by three-axis accelerometers located on the science telescopes and at the instrument mounting feet. The jitter team used the collected data to extract transfer functions, structural damping ratios, and the HGA hinge stiffness. The SDO test plan also included assembly level tests that provide results for validating the jitter analysis process and the structural finite element model.

The HGA assembly test consisted of two HGA proto-flight gimbal mechanisms, the flight HGA dish, and other flight-like supporting structures. The jitter team measured the HGA induced disturbance forces and torques at the mounting interface of the HGA assembly, as well as performed tap tests for updating HGA structural model. The structural verification unit (SVU) is a duplicate of the flight structure and was used in conjunction with a flight reaction wheel to test the disturbance levels generated by the wheel. The SVU-flight wheel test data show that the analysis prediction is conservative by a factor about 1.5 to 2. Additional spacecraft damping information was also extracted from SVU stinger tests which demonstrate that the damping ratio (0.3%) used in the jitter analysis was reasonable. The jitter team has begun to develop on-orbit contingency plans in order to protect the observatory jitter performance against model uncertainties.

Lunar Reconnaissance Orbiter (LRO)

(POC: Joe Garrick, Joseph.C.Garrick@nasa.gov and Mark Beckman, Mark.Beckman@nasa.gov)

Introduction

As part of the Robotic Exploration Program (RLEP), the Lunar Reconnaissance Orbiter (LRO), which is shown in Figure 29, represents the first of a series of unmanned exploration spacecraft to the Moon with the goal of using the information gathered to establish a permanent manned presence. The FDAB provides extensive support to LRO in the areas of mission design, orbit and attitude determination, and onboard control systems development.

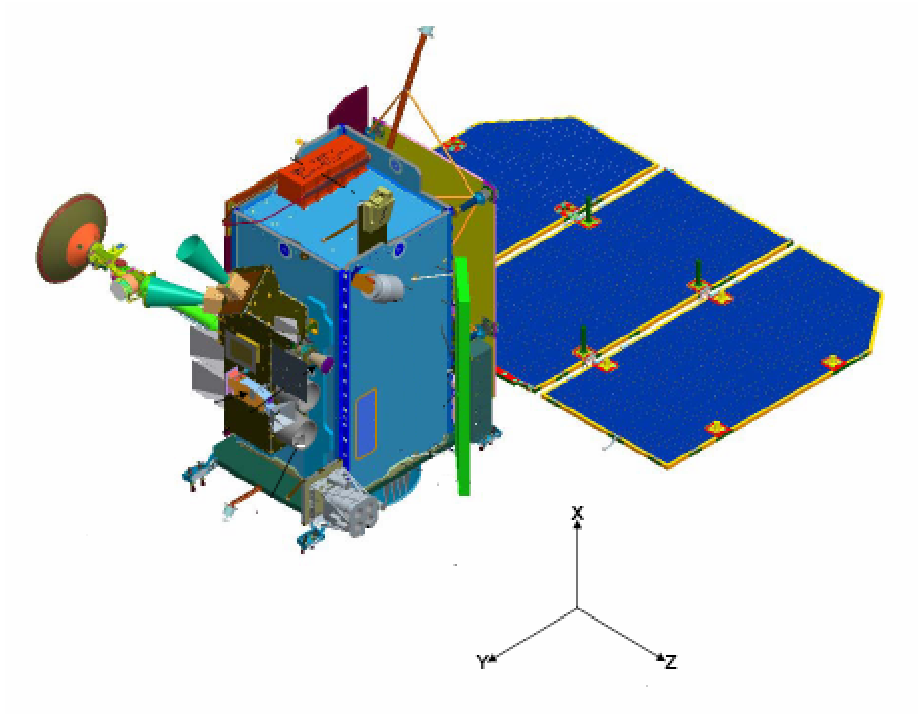

Figure 29: Fully-Deployed LRO Spacecraft

The FDAB is providing all mission design, maneuver planning and orbit determination support for LRO. In 2006, the Flight Dynamics team supported many project reviews including the Mission Preliminary Design Review (PDR), Delta-GN&C PDR Peer Review, Lunar Orbit Insertion (LOI) Peer Review, GN&C Critical Design Review (CDR), and Mission Critical Design Review. Significant achievements in 2006 included detailed analysis of the first Lunar Orbit Insertion (LOI) maneuver to support the LOI Peer Review and development of the complete launch window and launch vehicle targets.

Lunar Orbit Insertion

LOI-1 is the most critical LRO maneuver. Nominally LOI-1 captures LRO into a 5-hr lunar orbit. LOI-1 is designed to allow for many different contingencies including premature termination of the LOI-1 maneuver. Depending on the duration of the LOI-1 maneuver prior to termination, LRO can be in a wide range of orbits. Roughly, any duration greater than half the planned duration is sufficient to safety capture about the Moon. Any duration less than about a third puts LRO into a hyperbolic trajectory (swingby) past the Moon. The flight dynamics team has come up with a Deep Space Maneuver (DSM) plan to still achieve lunar orbit 60 days later even with a lunar swingby at LOI-1. LOI-1 durations between stable lunar capture and lunar swingby are weakly captured and require an immediate restart of the LOI-1 maneuver. Without the restart, the weakly captured spacecraft will dramatically change inclination due to third-body effects and will never to able to recover a polar orbit. The resulting trajectory, in the event that the DSM plan is needed, is shown in Figure 30.

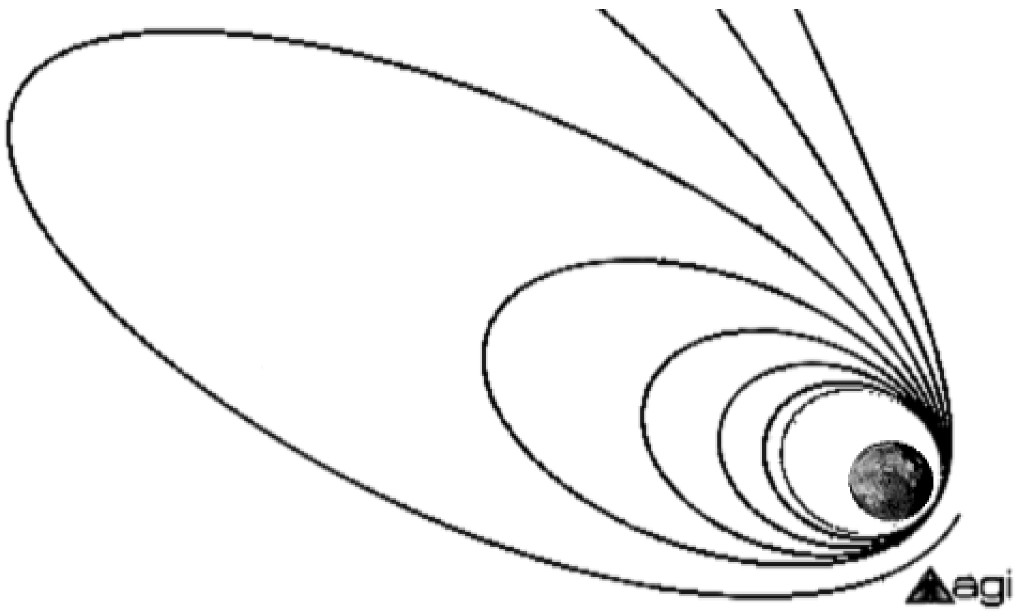

Figure 30: Premature LOI-1 Termination Orbits

<u>Launch and Early Operations</u>

LRO will be launched on an Atlas V 401 two stage launch vehicle (LV) on a direct lunar transfer. After Main Engine Cut-Off (MECO) -1, there will be a short coast phase to place the Transfer Trajectory Insertion (TTI) at the proper geocentric latitude to set the outgoing asymptote. At this point, the Centaur upper stage will re-ignite and place LRO onto the direct lunar transfer orbit. The lunar transfer trajectory is a minimum energy transfer to the Moon. There are two launch opportunities per day for a minimum energy direct transfer to the Moon: a short coast and a long coast. LRO has no requirement to use exclusively either the long or short coast solution. However, due to LV restrictions, only one of the two opportunities per day will be used. The choice between the daily short or long coast solutions depends on many factors, including eclipse time during transfer phase and time to first ground station acquisition. In addition, LRO has a science constraint to be at a beta angle of less than 20 degrees (Sun within 20 deg of lunar orbit plane) at the time of lunar solstice. This constraint limits the launch window to about two to three consecutive days every two weeks. With these constraints, LRO has 14 launch days available in the fall of 2008. The primary launch date is October 28, 2008.

ACS Analysis

The main activities during the past year for the Attitude Control Systems (ACS) engineers were to produce attitude related requirements and to implement the preliminary design for the onboard flight software attitude and orbit control algorithms. The onboard control algorithms are functionally responsible for managing the spacecraft's attitude pointing, orbit insertion and maintenance, and the accurate pointing of the high gain antenna and solar array during all phases of the mission. The algorithms are implemented and validated by the ACS engineers in a high fidelity time domain simulator that accurately represents the control laws, dynamics, sensors, actuators and environmental models. After thorough investigation, the attitude and orbit control algorithms were delivered to the flight software engineers for coding and are undergoing testing.

The requirements that drive this design were produced by the ACS analysts after extensive research, analysis and discussions with other LRO subsystems and manufacturers of ACS related hardware. In conjunction with being used to develop the onboard control algorithms, requirements produced by the ACS team were also used to procure the ACS sensors (coarse sun sensors, star trackers and inertial reference unit) and actuators (reaction wheels and thrusters). Later these requirements will be used to validate the performance of the ACS algorithms and hardware during testing phases, of which the ACS engineers will provide analytical support. As for the sensors and actuators, the ACS engineers worked closely with the ACS hardware engineers to make sure potential hardware manufacturers understood the requirements and operational considerations for the LRO mission. During the past year contracts were awarded to manufacturers and ICDs received for each of the ACS sensors and actuators.

The FDAB also began to provide support during the past calendar year in developing requirements for the Attitude Ground System (AGS) software. The AGS is responsible for definitive attitude determination and verification, calibration of ACS sensors and HGA, and the production of attitude related mission products. Requirements for the AGS were produced during the past year from the Project and ACS level requirements and operational considerations. The design and development of the AGS will begin in calendar year 2007.

ACS Critical Design Review

The highlight of the year was the successful presentation of all the ACS teams efforts at the mission level Critical Design Review (CDR). The ACS presented results that demonstrated the control algorithms met stability and performance requirements. The high fidelity simulator developed by the ACS engineers was used to produce thousands of Monte Carlo simulations to demonstrate successful performance of the controllers under various and random initial conditions. Other key analysis presented by the ACS engineers at the CDR included a multi-body dynamics simulation used to characterize jitter disturbance due to HGA, solar array and reaction wheels, simulations used to model the effects of fuel slosh during periods of acceleration, to demonstrate the duty cycle performance for all thruster activities from orbit insertion to routine orbit maintenance to ensure meeting of thruster manufacturers specifications, to characterize the affects of center of gravity migration over the mission on thruster controller performance, and ACS error budgets and corresponding analysis to demonstrate that control modes and HGA pointing are with requirement allocations.

Magnetospheric Multi-Scale Mission (MMS)

(POC: Cheryl Gramling, Cheryl.J.Gramling@nasa.gov)

Introduction

The Magnetospheric Multi-Scale Mission (MMS) consists of four spinning spacecraft flying in a tetrahedral formation in highly elliptical earth orbits to study the phenomenon of magnetic reconnection on the dayside magnetopause and the nightside neutral sheet. A mission of this type has never been developed nor operated at GSFC before and presents many challenges to both pre-and post-launch flight dynamics support.

MMS is currently in phase A as an in-house development effort. Over the past year and a half, the FDAB team developed reference trajectories for nine launch opportunities spaced throughout one year, formations for each separation in each mission phase, performed error analysis to determine the stability and delta-V associated with formation maintenance, and provided a navigation concept of operations and supporting analysis. The full suite of analyses was presented at the Mission Definition Review (MDR) held in September 2006. In November 2006, we held an Independent Peer Review of the flight dynamics focusing on formation flying. Analysis of the mission operations concept that resulted in 200 maneuvers per spacecraft over the mission lifetime coupled with feedback from the Peer review team indicated a need for a revised operations concept. Since that time, MMS has been given direction to descope the mission. A significant portion of the descope effort involves flight dynamics analysis of new reference trajectories and formations.

Reference Orbits

(POC: Marco Concha, Marco.A.Concha@nasa.gov)

Development of a catalog of reference orbits that satisfy the science requirements and meet mission objectives has been accomplished through analysis and simulation. Analyses include the specification of insertion conditions necessary to minimize orbit apogee latitude while ensuring science observations at the dayside magnetopause and achieving dwell time goals about the magnetosphere neutral sheet. In addition, the simulation of the maneuvers necessary for plane change and orbit raising was performed in order to estimate the delta-v required for the mission. Modeling of various system-level and science constraints were applied throughout the analyses.

At the onset of each reference orbit study, several candidate orbits at insertion are considered. These candidate orbits are fixed in size and inclination. A parametric scan of all available argument of perigee values is performed for each candidate orbit across a 12-month launch opportunity period, with one launch date selected every 30 days. For each case the Right Ascension of Ascending Node is then selected to minimize the apogee latitude during the first science period of interest. Science Goal metrics are cataloged, and operational constraints that limit eclipse shadow duration and expended delta-v are applied. Cases that fail to reach the science goals and exceed constraint limits are discarded.

For the initial MMS study, additional maneuver phases added to the overall complexity of the mission design. Late in the calendar year 2006 a scale back, or de-scope of the mission design was requested that greatly reduced the mission maneuver complexity with regard to the reference trajectory. A mission design eliminating various orbit raising phases was proposed and investigated. Currently, this mission design approach is undergoing a second iteration, dubbed "Descope-02".

Formation Flying
(POC: Steven Hughes, Steven.P.Hughes@nasa.gov)

During the course of the year, the FDAB designed formations for all phases of MMS, meeting all mission requirements, and performed formation stability analysis and characterized expected maneuver frequencies and magnitudes in presence of navigation and control errors. At the MMS Mission Design Review, flight dynamics team members presented the formation flying concept for establishing and maintaining formations. Additionally, they held a Formation Flying Review, assembling a team of independent experts from academia, NASA, and ESA to review their formation flying design work for MMS. This review was held very early in the design process to get feedback while we can still make significant design changes. They received a lot of good feedback and incorporated and plan to make many of the suggested changes in the next phase of the project.

Navigation
(POC: Russell Carpenter, Russell.Carpenter@nasa.gov)

Based on the trade study "Onboard vs Ground Orbit Determination for MMS" we performed in the fall of 2006, MMS will perform navigation onboard using GEONS, embedded within the Inter-spacecraft Ranging and Alarm System (IRAS). The IRAS provides GPS and inter-spacecraft ranging data types to GEONS, and GEONS may also process one-way forward Doppler derived from TDRSS and/or DSN contacts. The MMS navigation team delivered several reports and memoranda describing our analysis of this concept during FY2006.

We delivered "Magnetospheric Multiscale (MMS) Mission Navigation Concepts Analysis." This report summarizes the results of an analysis of several different navigation concepts. The results contained in this report include both absolute and relative navigation accuracies that are achievable for three different phases of the mission and three different formation sizes (e.g. Phase 1 10 km, Phase 1 1000 km, Phase 2b 10 km, Phase 2b 1000 km, and Phase 3c 15 km). The different tracking measurements considered are one-and two-way Ground Station Doppler, one- and two-way cross-link ranges, and GPS pseudoranges.

We delivered "Updated MMS Concepts Analysis Based on the Phase-2b 10-Kilometer Formation Using Refined IRAS Models." This report summarizes the results of an analysis of several candidate navigation scenarios for the MMS mission. The results contained in this report include both absolute and relative navigation accuracies that are achievable for the case of the Phase 2b formation with a 10-kilometer spacecraft separation. The different tracking measurements that were considered are one- and two-way crosslink ranges and GPS pseudoranges. This report also discusses issues related to the data latency arising from the navigation data packet exchange cycle among the member satellites and the four-second crosslink measurement cycle.

We delivered “Notes on MMS Deployment.” This memorandum summarized separation strategies for some other multi-satellite missions, described considerations for MMS separation, and developed a starting point for future work on MMS separation.

We delivered “IRAS Descope Options.” This memorandum responds to direction from the MMS Mission Systems Engineer to compare and contrast possible descope options for the IRAS, including no IRAS, an augmented transceiver, a transponder, and a GPS-only version of the current IRAS. This memorandum helped to remove IRAS de-scopes as a viable candidate for MMS cost savings.

We delivered the memorandum “TRL6 Guidelines for MMS IRAS,” which listed the broad conditions under which the MMS IRAS can be considered to have been validated in a relevant environment.

<u>MMS ACS</u>

(POC: Dean Tsai, Dean.C.Tsai@nasa.gov)

Magnetospheric Multiscale is the first formation flying mission of its kind, where spinning spacecraft were used and where the control of the relative and the absolute orbit states were held to a high level of accuracy. Failing to achieve the designed orbit states would result in additional fuel cost and enormous amount of manpower. Such a concern has been the driver for MMS ACS design for the past two years.

In 2006, MMS ACS team extended the MMS spacecraft model from a single point-mass model to a multi-rigid-body model. The spacecraft model was broken down to the core body and segments of six booms, some are radials and some are axial with respect to the spin-axis. Each segment was assumed to be rigid and was linked to other links via a 3 rotational degree-of-freedom joint. The extension was necessary to accurately capture the nonlinear core body dynamics when there was energy exchange between it and its appendages as the system spins in space. The model was created in a homegrown dynamics simulator, Sim42, which is written in C and the source codes are readily available for customization. The simulation results were compared with Laboratory for Atmospheric and Space Physics (LASP) of University of Colorado through the science team collaboration. After several iterations, the results from the LASP’s SimMechanics based model had matched with the results from MMS ACS. The comparison between the models is shown in Figure 31.

During one of the simulation comparison run, the team had discovered a potential issue with the safety of one of the instrument due to the inadequate frequency separation between the structural resonance and the control bandwidth (see Figure 32). The discovery had spawned a series technical discussion and numerous instrument safety reviews. The ongoing effort going into year 2007 is a multi-latitude approach, where the instrument team is devising ground tests further identifying the system parameter while leaving the option of redesign to the project.

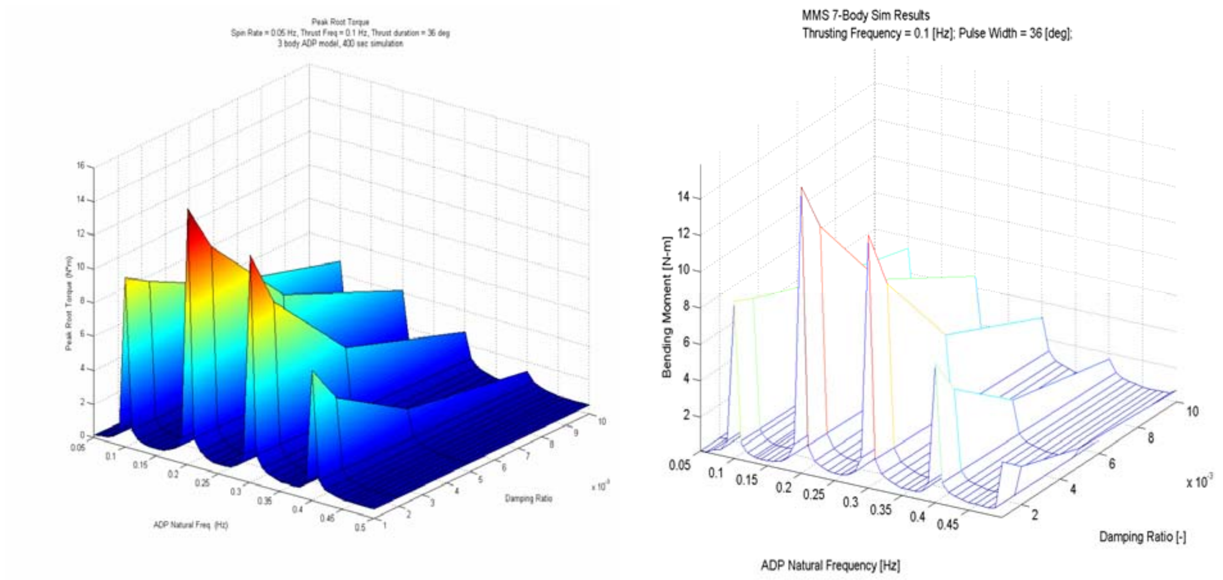

Figure 31: Validation of MMS ACS and LASP Models

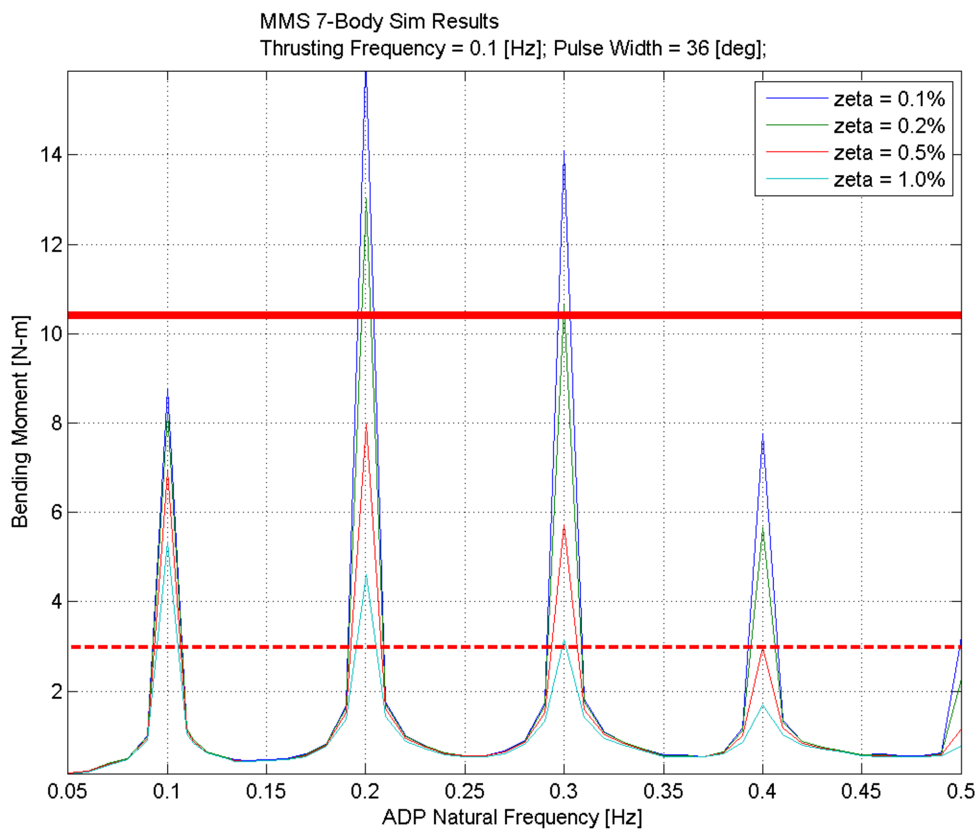

Figure 32: Axial Boom Natural Frequency vs Bending Moment

Other MMS ACS achievement included the successful completion of Phase-A analysis, the successful completion of the Mission Definition Review, and a comprehensive fuel budgeting exercise.

Global Precipitation Measurement (GPM)

(POC: John Van Eepoel, John.M.VanEepoel@nasa.gov)

The Global Precipitation Measurement (GPM) Mission seeks to analyze rainfall amounts over the entire globe. This mission follows on the highly successful TRMM mission in making similar measurements, and picks up where TRMM left off. GPM will measure rainfall totals from +/- 60 degree latitude, whereas TRMM measured between +/- 35 degree latitude. The design of the spacecraft is wholly responsible of the project office at GSFC, however, many subsystem designs are being done by contractor partners. The GN&C subsystem is one that will be designed and built by a contractor partner, but eventually integrated at GSFC. The project for the past year has requested analysis assistance from the MESA (590) division to provide GN&C analysis in support of trade studies and system decisions in preparation for selection of the contractor partner. The team in the MESA division over the past year has designed and analyzed several control modes to assess the environment of the mission, the actuator complement necessary to perform the mission and provide a baseline for the placement of actuators. The control modes designed include a nominal science pointing mode, a Safehold mode design, and a Delta-V mode design and provided stability analyses for these modes as well as shown that the mode designs meet mission requirements. In addition to control mode designs, the GN&C analysis team has analyzed the jitter environment of the mission utilizing an initial structural model provided by the GPM Mechanical team, and models for the major disturbances of the mission, which has focused on the GMI instrument imbalance and its interaction with the solar arrays. The GN&C team has provided support for analysis, review consultation, and intends to support the project through the selection of the contractor partner. The GN&C team will continue to provide jitter analysis for the life of the mission since this is viewed as a system level concern, and one that is out of the scope of the GN&C contractor.

Flight Dynamics Facility

(POC: Sue Hoge, Sue.L.Hoge@nasa.gov)

The FDAB Flight Dynamics Facility (FDF) provides flight dynamics operations services for robotic missions, Expendable Launch Vehicles (ELV) and the Space Transportation System (STS) that include: trajectory support, mission design, analysis and orbit maneuver support, orbit determination and contact acquisition aids, and tracking data evaluation. Highlights of FDF activities in 2006 are given below.

General

The Flight Dynamics Users Council was formed in 2005 as part of our continuing effort to provide high quality, efficient and cost-effective support to our customers. The group is composed of major FDF customers and meets at least twice each year to discuss support services, budget and upgrade/improvement efforts. Meetings in 2006 were held in February, June and September.

Missions

The operations tempo within the facility was very high in 2006. The area of Human Spaceflight included mission support for STS-121 (July 2006), STS-115 (September 2006) and STS-116 (December 2006). Also supported was the Soyuz-12S mission (March 2006) and Soyuz-13S mission (September 2006). Regular International Space Station (ISS) support was performed in 2006 which included on-orbit support and maneuvers as well as testing and simulations.

The FDF had a full year of Expendable Launch Vehicle (ELV) support in 2006. The facility supported 5 SeaLaunch, 2 Atlas, 2 Delta and 4 other launch vehicle platform launches in 2006, including pre-launch analysis, testing and simulation support. FDF personnel received the Goddard Excellence Award for Customer Service as part of the ELV team.

Several high visibility missions were supported by the FDF in 2006. In February, FDF supported the Space Technology 5 (ST-5) mission, which was launch on a Pegasus launch vehicle from Vandenberg Air Force Base (AFB). The FDF provided pre-mission analysis and support including testing and simulation, and was very involved in on-orbit operations. Support on orbit included predictive orbit ephemeris, data in the Deep Space Network (DSN) Inter Center Vector (ICV) format for DSN scheduling and tracking services, osculating elements for Air Force support sites, short and long term planning products, and processing of X-band tracking data. When the ST-5 mission experienced on-orbit anomalies, the FDF provided contingency support by analyzing additional tracking data and providing a higher frequency of support products.

In May, FDF successfully supported the Calipso-CloudSat mission in cooperation with the Centre national d'études spatiales (CNES, France). FDF support included pre-launch analysis, launch support, and on-orbit support for spacecraft acquisition. Also, the FDF supported early orbit operations for the GOES-N mission. Support included the creation and transmission of acquisition data and anomaly support on-orbit.

The STEREO mission launch successfully in October of 2006, and the FDF was heavily involved in the pre-mission analysis, testing and simulation and on-orbit support for this mission. The FDF provided on-orbit support in the form of acquisition vectors and ephemeris for the DSN and the Mission Operations Center (MOC) for the early orbit, lunar swing-by and heliocentric phases of the mission.

Attitude Operations Transition to SOHO & WIND MOCs

The SOHO and WIND missions have been extended beyond their planned lifetimes. The extended missions have minimal budget to expend on satellite operations and cost reductions were necessary across the Projects. The SSMO supported moving the attitude determination operations functions from the FDF to the Mission Operations Centers (MOCs) to reduce operations cost while still meeting mission requirements.

A team composed of FDF and MOC personnel developed the operations concept and designed the MOC architecture. The team moved the FDF hardware and software to the MOCs, and performed parallel testing to certify the attitude determination systems (ADSs) in the MOC. The transition was completed on March 31, 2007.

Systems

The FDF completed two major reengineering/upgrades during the 2006 calendar year. The first was the completion of the UNIX operating system upgrade to HPUX 11. This multi-phased, multi-year effort involved the recompiling of software systems and several months of testing. It was completed in September of 2006 without interruption of services to our operational customers.

The second major upgrade effort that was completed in 2006 involved the upgrade of ORACLE database software to 9i. This upgrade required a complete reconfiguration of the operational database as well as new database machines. This too was a multi-phase, multi-year effort that was accomplished without interruption of customer services. Completion of these upgrades made it possible for the FDF to dismantle and remove the FDDI ring that was part of the internal FDF network prior to the move. These updates to Matlab V6.5 for SOHO and WIND were completed and tested prior to the FDF hardware move and software deliveries to the MOC. However, excessive replacement costs and limitations in other required commercial software packages used for telemetry receipt/processing required that “vintage” HP UNIX 10.x operating system (OS) machines continue to be used for the ADS in the MOC. This limitation also precluded updating the Matlab software to the latest version, since it was not compatible with the 10.x OS.